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W. S. Gilbert and J. W. Rosengren

May 9, 1952

Berkeley, California

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ABSTRACT

The reaction $\gamma + D \longrightarrow p + n$ was investigated using the photon bremsstrahlung spectrum from the Berkeley 322 Mev electron synchrotron. Protons were detected by a scintillation counter telescope system consisting of three liquid scintillators, each viewed by two or three photomultiplier tubes. Two types of target system were used: high pressure, low temperature deuterium gas, and heavy water-with-water subtraction. Values for $\left(\frac{d\sigma}{d\Omega}\right)_\theta$ were determined at laboratory angles 30° - 90° for E_γ center of mass = 140 ± 15 Mev and 200 ± 15 Mev, and at laboratory angles of 30° - 115° for E_γ center of mass = 250 ± 15 Mev. The following total cross sections were determined:

$$\sigma_{total}\ (140) = 11.8 \pm 4.1 \times 10^{-29}\ \text{cm}^2$$

$$\sigma_{total}\ (200) = 10.0 \pm 3.0$$

$$\sigma_{total}\ (250) = 15.9 \pm 6.4$$

These uncertainties are standard deviations based on counting statistics only; there is an additional 40 percent absolute uncertainty.

These cross sections are far greater than the values predicted by theories which exclude the effects of meson interaction. However, a theoretical treatment which does take the specifically mesonic interaction into account does yield cross sections of a magnitude comparable with those observed.

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Introduction

The deuteron, by virtue of being a two body system, is of primary interest in nuclear theory since one might hope to determine its wave functions exactly. Ever since the theoretical papers of Bethe and Peierls[1] and Fermi[2], relating to the photodisintegration of the deuteron and its inverse reaction, the n-p capture process, numerous experimental studies have been carried out to test the theory and to determine specific parameters relating to the deuteron's binding energy, the shape, width and depth of the nuclear potential well. The majority of these investigations have been carried out at energies of a few Mev using naturally radioactive γ-emitters. Recently, work has been carried to approximately 20 Mev[3,4]. The information obtained from photodisintegration of the deuteron is similar to that obtained from neutron-proton scattering data at corresponding energies. At low energies the photodisintegration data give information about the effective ranges of the neutron-proton interaction but do not yield any information on the shape of the potential. Theoretical calculations have been carried out for γ-energies up to 150 Mev[5,6,7] using the best values for the parameters determined from other experiments such as n-p scattering. These high energy calculations depend on the shape of the potential and the percentage of charge exchange and are affected by the use of tensor forces. They should give a reasonable picture of the cross sections due to the photoelectric dipole and quadrupole moments of the nucleons; however, no calculation was made of the contribution of meson effects due to interactions with the virtual meson field.

The Berkeley synchrotron yields photons of energies (relative to the center of mass of the deuteron-photon system) up to about 280 Mev, and it appeared desirable to investigate the photoeffect at these high energies. By comparison with the theoretical treatments described above, one could expect to discover the magnitude of the contributions made to the cross section by meson interactions.

Kinematic Considerations

The reaction $\gamma + D \longrightarrow p + n$ represents a two body problem both before the photon interaction and afterwards. This being the case, it is possible to determine uniquely the energy of the initiating γ-ray by measuring the energy of the emergent proton and the angle of emission of this proton with respect to the incident γ-ray direction.

At high γ-energies it is possible for mesons to be produced along with two resultant nucleons and the final products then form a three body system. If one were to measure the energy and angle of only one of these emergent particles, he would not be able to determine uniquely the energy of the initiating γ-ray. However, because approximately 140 Mev of energy are required to create the meson and because of the kinematics of the conservation of momentum between the meson and any recoil nucleons, the energy of any such recoil nucleons would be relatively low.

In the case of our determinations of $\frac{d\sigma}{d\Omega}$ for $E_\gamma = 200$ Mev and $E_\gamma = 250$ Mev, our counters defined various proton energy intervals depending upon the angle. In all cases any recoil protons associated with meson production by even the 322 Mev quanta would be of lower energy than the interval defined by our counters. Therefore for these two energies it is energetically impossible for there to have been contribution from any meson producing reaction. In the case of $E_\gamma = 140$ Mev, at a few of the larger angles the maximum energy protons recoiling from produced mesons could enter the detection system. Since these protons are of a three body system, one cannot determine how many of the recoil protons lie in the range of acceptance even though the meson production rate is known. However, since the known meson production rate is smaller than the observed proton rate and since presumably only a small fraction of the meson events would lead to maximum energy recoil protons, the contribution from this process is considered negligible.

Description of the Experiment

The x-rays were produced in the Berkeley electron synchroton by letting the internal electron beam strike a 0.020 inch platinum target placed on the inner side of the accelerating donut. The beam was spread out in time by modulating the rf accelerating voltage such that electrons spilled into the target over a period of some 3000 μsec. In the "spread out" beam, the electrons are of various energies corresponding to the magnetic field at the time they strike the internal synchrotron target. The relative beam intensity over the 3000 μsec. period could be determined and the net bremsstrahlung distribution was found by combining the bremsstrahlung spectra corresponding to the various quantum limits (electron energies) weighted by the relative beam intensities at these electron energies.

In Fig. 1 is shown the deuterium gas target arrangement. At 55 inches from the platinum target the beam was collimated by a tapered hole in a lead block 9 inches thick. The collimating hole was a half-inch in diameter at the entrance end and was part of a cone whose apex lay at the platinum target. Directly behind the primary collimator was the 6 inch thick lead secondary collimator which had a 1 inch hole. Behind this and directly in front of the experimental target was a tertiary collimator of lead, 6 inches thick and with a 2 inch hole. The target and collimators were aligned by means of a transit. Photographs of the beam were then taken with a 1/8 inch primary collimator and a final alignment of the target was made with respect to this small, well defined beam. Then the larger primary collimator was replaced. At the end of a run the 1/8 inch collimator was again inserted and photographs taken. The target proved to be still aligned at the end of each run.

The target (see Fig. 1) employed at E_γ = 200 Mev and 250 Mev was deuterium gas at a pressure of 2000 P.S.I. and at liquid nitrogen temperature (77° K) used in a line target assembly designed by R. S. White[8]. The walls of the gas target combined with the thickness of the first counter, however, represented so much absorber that protons initiated by 140 Mev γ-rays would not reach the second counter of the detection system. Therefore in order to investigate the cross section at 140 Mev, it was necessary to use a target whose self absorption was small. Heavy and ordinary water targets, 0.20 inch thick, were used for this purpose. Energetically, Compton protons from hydrogen are of too low an energy to give a count in our detection system. Therefore it was concluded that the entire counting rate from regular water could be considered as being due to the oxygen present. Subtracting this number from the counting rate due to heavy water yields the deuterium contribution alone. The regular and heavy waters were interchanged between the two containers several times to eliminate the effect of any difference in thickness of the two target holders. The cross section for photoprotons from oxygen is several times larger than that from deuterium and the statistics of the subtraction are extremely unfavorable. Thus at higher energies where it was energetically possible to use the high pressure deuterium gas target, it was statistically advisable to do so.

The counter telescope was placed in a lead house with 4 inch thick walls in order to be shielded from the general beckground of electrons and x-rays which pervade the magnet room of the synchrotron. A hole in the front wall of the lead house served as one defining aperture in the proton collimator. In the case of the deuterium gas system, the source of protons was a line target and it was necessary to define the target volume by a collimator system preceding the counter telescope. The value of effective target volume combined with the effective counter solid angle was obtained by a graphical integration for each proton angle. The angular resolution of the collimation system was such that the bulk of the protons accepted from the gas target were in the angular range $\theta \pm 4^\circ$. However, a few protons were accepted from between $4^\circ - 6^\circ$ from θ. Therefore the overall angular resolution was $\pm 6^\circ$ from the gas target. From the water targets the overall angular resolution was $\pm 4^\circ$. At each proton angle at which the counter telescope was placed a copper absorber was inserted before the counter with thickness appropriate to the proton angle and the desired photon energy.

To monitor the beam, three ionization chambers, two in front and one in back of the target, were used simultaneously. Their ratios were observed to remain constant throughout the experiment. The absolute calibration of the beam was due to Blocker and Kenney[9,10]. The uncertainty in the absolute calibration at the time of this experiment was estimated to be 30 percent.

Proton Detection and Identification

The protons were identified essentially by their range and dE/dx. A counter telescope consisting of three counters in line was employed. A particle's range was specified by demanding that it pass through the first counter and stop in the second. All three counters were connected in a coincidence circuit and the first two counters were connected in a separate double coincidence circuit. A subtraction of the two coincidence rates gave the rate of particles stopping in the second counter. The protons were then distinguished from other particles by the pulse height in the first counter.

The counters were liquid scintillators of terphenyl dissolved in toluene. The first counter, in which the particle's dE/dx was determined was three inches in diameter, 1.6 gm per cm^2 of toluene in thickness, and was viewed from the side by three 1P21 photomultiplier tubes with outputs connected in parallel. Counter 2, which consisted of 0.86 gm per cm^2 of liquid, and counter 3, which was 1.1 gm per cm^2 thick, were both four inches in diameter and were each viewed by two 1P21 photomultiplier tubes. 2.6 gm per cm^2 of copper absorber were permanently placed between counters 1 and 2 to improve the discrimination of the telescope. The pulses from the phototubes were fed to a pulse height discriminator and gate former. The gate length, the recovery time, and the resolution time were all about 0.4 μsec.

For particles of different masses and identical residual ranges, it can be shown that the ratio of the (dE/dx)'s in traversing matter is approximately $(m_1/m_2)^{0.44}$. In the case of protons and mesons, this ratio equals 2.30. This means that a proton would give up 2.30 times as much energy in Counter No. 1 as would a meson, and if the scintillators were perfectly proportional, the proton pulse would be 2.30 times as large as the meson pulse. This ratio, call it the merit ratio, is a limiting maximum since it holds only for identical residual ranges or, to put it another way, for a second counter of zero thickness. In practice, Counter No. 2 was of finite thickness and the ratio of the smallest proton pulse to the largest meson pulse was calculated to be 1.83. For protons the band of energies accepted was 62.5 - 71.0 Mev, with the corresponding energies given up in the first counter being 20.5 - 17.0 Mev, respectively. For mesons the band was 28.0 - 32.0 Mev, and the energy lost in the first counter was 9.3 - 8.0 Mev, respectively. To examine higher energy particles, a copper absorber was inserted between the target and the counter telescope.

To ascertain the conditions under which one would be counting protons with full efficiency, a run was made using the 90 Mev neutron beam of the Berkeley 184-inch synchro-cyclotron. This neutron beam is obtained by deuteron stripping and has a wide spread in energy (a total width at half maximum of about 30 Mev). This beam was used to bombard a paraffin target, and since the energy is below the threshold for meson production, the particles observed will be almost entirely protons with a small fraction of heavier particles. The curve giving counting rate per unit beam vs. photomultiplier high voltage is shown in Fig. 2. The arrow indicates a standard point on the curve. The operating conditions of the first counter at this point were made reproducible by determining the singles counting rate of this counter with a beta source in a standard geometry.

To be able to count the betas a standard 20 db attenuator, present in the output of the first counter during proton detection, was removed.

In Fig. 3 is shown the integral bias curve of coincidence counting rate vs. discriminator bias of the first counter obtained at 60° from a carbon target in the 322 Mev x-ray beam of the synchrotron. The arrow indicates the calibration point obtained using the 90 Mev neutron beam. The dotted curve indicates an ideal integral bias curve when there are only protons and π mesons. The maximum proton pulse is arbitrarily taken as shown and the other points are calculated from range energy relations. The absolute values taken for the proton and meson production are based on the experimental data of Keck[11] and of Peterson, Gilbert and White[12], respectively.

The observed curve from carbon is affected by electrons at the low bias end and perhaps by deuterons at the large bias points.

An operating point was selected at a bias five volts lower than the calibration point from the cyclotron run. From comparison of the ideal curve and the observed curve, we believe that only protons were counted at the operating point and that the protons were counted with full efficiency. A more detailed investigation in the low bias region (considerably beyond the operating point for proton counting) indicated a meson plateau. It was possible to measure a meson yield as a function meson energy which was in fair agreement with previous experimental data[12].

Results

The experimental values for the differential cross section are plotted in Figures 4, 5, and 6 as a function of proton angle in the center of mass system. These values have been corrected for attenuation of the protons by nuclear interaction in the copper absorbers used to fix the proton energy. The cross section for this was taken to be equal to the geometrical nuclear area taking the nuclear radius to be $1.4 \times 10^{-13} A^{1/3}$ cm. These data have also been corrected for loss to the detection system of protons due to small angle multiple coulomb scattering in the absorbers. The effect of penetration of the protons through the edges of the collimator system was calculated to be negligible.

It is to be noted that the uncertainty in the photon energy due to the angular and energy intervals presented by the counter telescope is different for each angle; however, an average overall uncertainty of 15 Mev has been assigned.

The uncertainties shown are standard deviations based on counting statistics only, including the subtraction of background taken with the empty target assembly, and should be the total uncertainties in all the relative values. There is, however, an additional standard deviation of about 40 percent (assuming the nuclear absorption correction to be exactly correct) to be assigned to the absolute cross sections because of uncertainties in beam calibration, effective thickness of the second counter, scattering corrections etc. In addition it should be noted that the 140 Mev data were taken at a considerably later date with a different geometry, and so the accuracy of this point relative to the 200 and 250 Mev points is suspect.

The total cross sections were obtained by integrating under the arbitrarily assumed curves shown drawn through the differential cross section data in Figures 4, 5 and 6. The results are given in Table I. The uncertainties are standard deviations based on counting statistics only. It should be recalled that all these cross sections are for photo dissociation of the deuteron where a meson is not produced.

There is an uncertainty due to the extrapolation over angles for which the differential cross sections were not obtained. Since the solid angle and apparently also the differential cross sections are small at most of the angles not investigated the error due to this extrapolation should be small.

TABLE I

Photon Energy (Center of Mass)	Total Cross Section
140 Mev	$11.8 \pm 4.1 \times 10^{-29}$ cm^2
200 Mev	10.0 ± 3.0
250 Mev	15.9 ± 6.4

These values of the total cross section are plotted in Fig. 7 along with the theoretical curves of Marshall and Guth[7], calculated for an exponential shape potential and for a Hulthen potential, their results being essentially the same as those of Schiff[6]. Their calculations take only the nucleon electric dipole and quadrupole transitions into account and ignore the transitions which involve meson effects. It is seen that the experimental cross sections are much higher than such theoretical predictions indicating a sizeable contribution from mesonic processes. These high experimental values are in fair agreement with the results obtained by Kikuchi[13], who investigated the photo-dissociation of the deuteron at high energies using nuclear emulsions. The data obtained at 140 Mev do not agree too well with that obtained by Benedict and Woodward[14] who measured $d\sigma/d\Omega$ for deuteron dissociation at 60°, 90°, and 120° in the laboratory frame up to about 160 Mev. Our values at 60° and 90° are about a factor of three higher at 140 Mev.

Preliminary calculations by Huddlestone and Lepore[15] using a pseudoscalar theory show that the meson exchange contributions to the disintegration process can be large enough to explain these experimental data. Recently Austern[16] has made some preliminary calculations of deuteron photo-dissociation using a nucleon isobar model which are in rough agreement with our values for total cross section.

One can conclude that the cross section for deuteron photodisintegration at high energies (140 Mev and above) is much larger than predicted by theories ignoring mesonic interactions. These data combined with those of Kikuchi[13] strongly indicate that above the threshold for meson production the cross section actually increases with energy.

Acknowledgements

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FIGURE CAPTIONS

Fig. 1 Diagram of experimental arrangement using deuterium gas target (actually only one counter telescope was used).

Fig. 2 Coincidence plateau for detection of protons produced by bombardment of paraffin with the cyclotron 90 Mev neutron beam.

Fig. 3 Integral bias curve for detection at 60° of protons produced by bombardment of carbon with 322 Mev bremsstrahlung.

Fig. 4 Differential cross sections in the center of mass frame for photo-dissociation of the deuteron, $E_\gamma = 140$ Mev (center of mass).

Fig. 5 Differential cross sections in the center of mass frame for photo-dissociation of the deuteron, $E_\gamma = 200$ Mev (center of mass).

Fig. 6 Differential cross sections in the center of mass frame for photo-dissociation of the deuteron, $E_\gamma = 250$ Mev (center of mass).

Fig. 7 Total cross sections for photo-dissociation of the deuteron.

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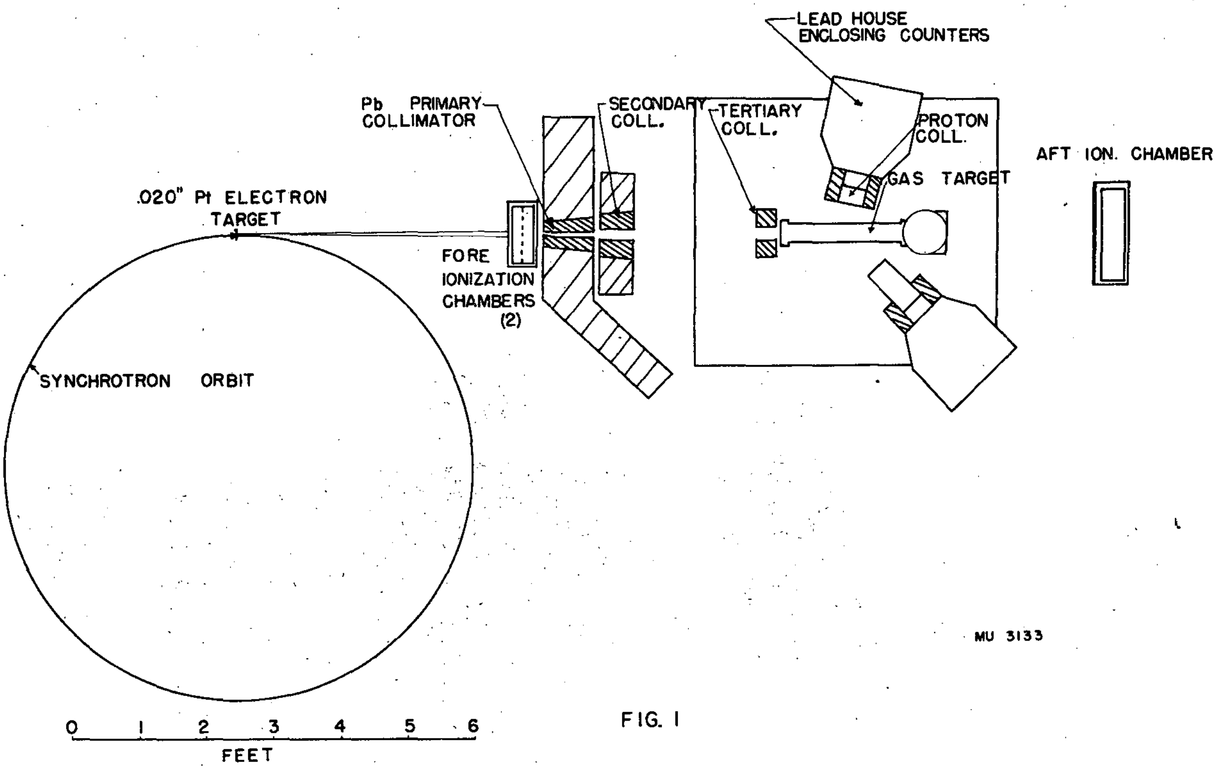
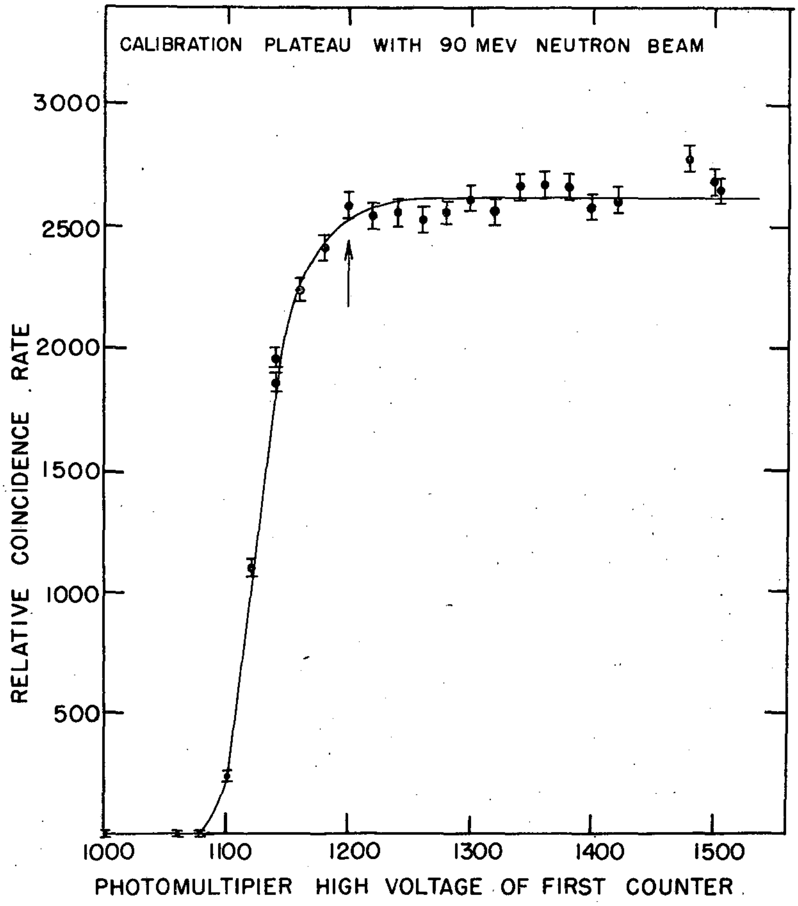

LEAD HOUSE
ENCLOSING COUNTERS
Pb PRIMARY
COLLIMATOR
SECONDARY
COLL.
TERTIARY
COLL.
PROTON
COLL.
GAS TARGET
AFT ION. CHAMBER
.020" Pt ELECTRON
TARGET
FORE
IONIZATION
CHAMBERS
(2)
SYNCHROTRON ORBIT
0
1
2
3
4
5
6
FEET
MU 3133
FIG. I

Fig. 1


CALIBRATION PLATEAU WITH 90 MEV NEUTRON BEAM
3000
2500
2000
1500
1000
500
RELATIVE COINCIDENCE RATE
1000
1100
1200
1300
1400
1500
PHOTOMULTIPIER HIGH VOLTAGE OF FIRST COUNTER

MU3476

Fig. 2

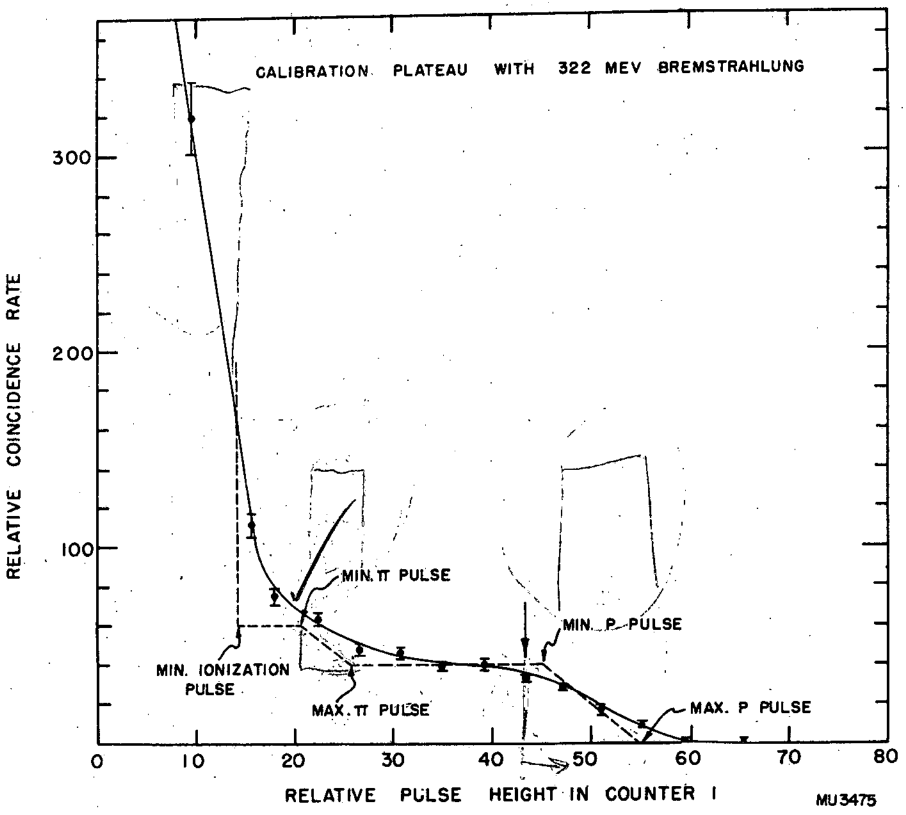
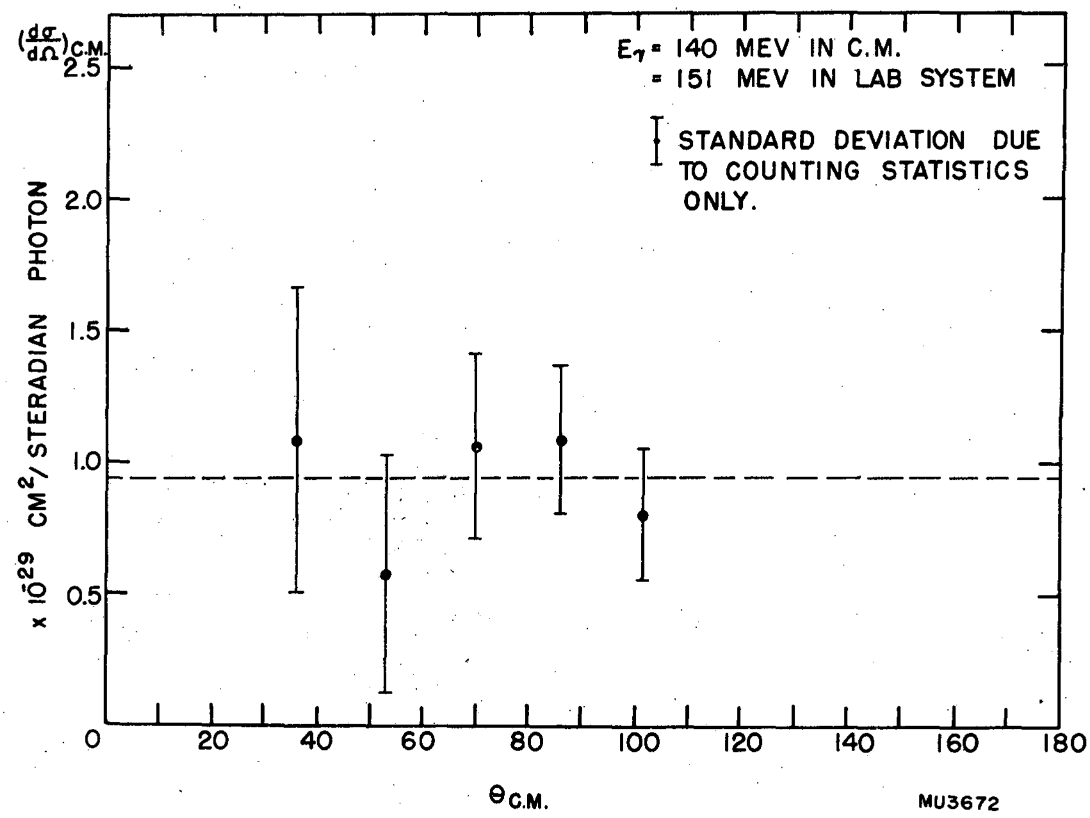

CALIBRATION PLATEAU WITH 322 MEV BREMSTRAHLUNG
RELATIVE COINCIDENCE RATE
300
200
100
MIN. π PULSE
MIN. P PULSE
MIN. IONIZATION PULSE
MAX. π PULSE
MAX. P PULSE
0
10
20
30
40
50
60
70
80
RELATIVE PULSE HEIGHT IN COUNTER I
MU3475

Fig. 3



$(\frac{d\sigma}{d\Omega})_{C.M.}$
2.5
2.0
1.5
1.0
0.5
x 10^{-29} CM^2/STERADIAN PHOTON
0
20
40
60
80
100
120
140
160
180
$\theta_{C.M.}$
E_γ = 140 MEV IN C.M.
= 151 MEV IN LAB SYSTEM
STANDARD DEVIATION DUE TO COUNTING STATISTICS ONLY.
MU3672

Fig. 4

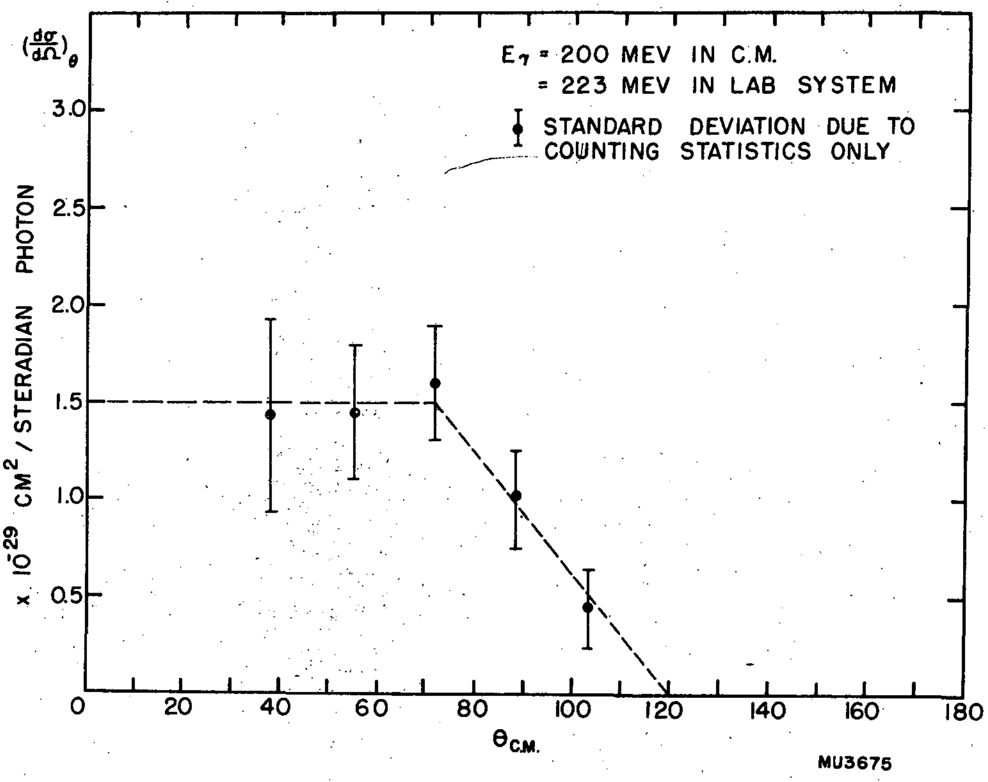

$(\frac{d\sigma}{d\Omega})_\theta$
x 10^{-29} CM^2 / STERADIAN PHOTON
3.0
2.5
2.0
1.5
1.0
0.5
0
20
40
60
80
100
120
140
160
180
$\theta_{C.M.}$
E_γ = 200 MEV IN C.M.
= 223 MEV IN LAB SYSTEM
STANDARD DEVIATION DUE TO COUNTING STATISTICS ONLY
MU3675

Fig. 5

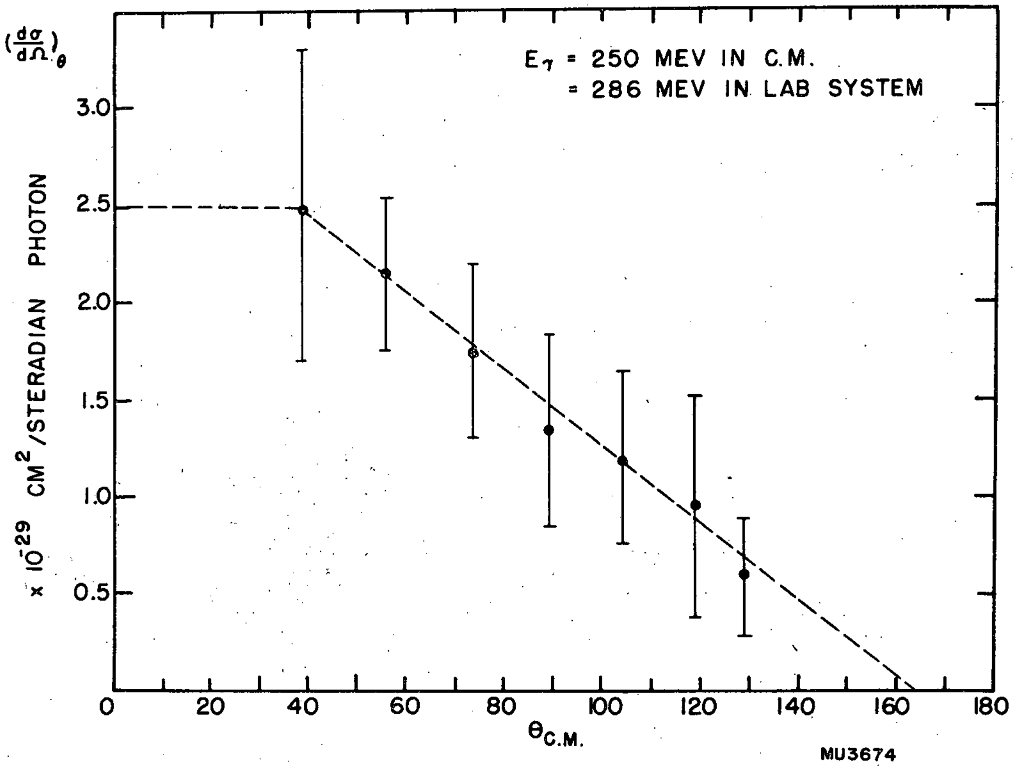
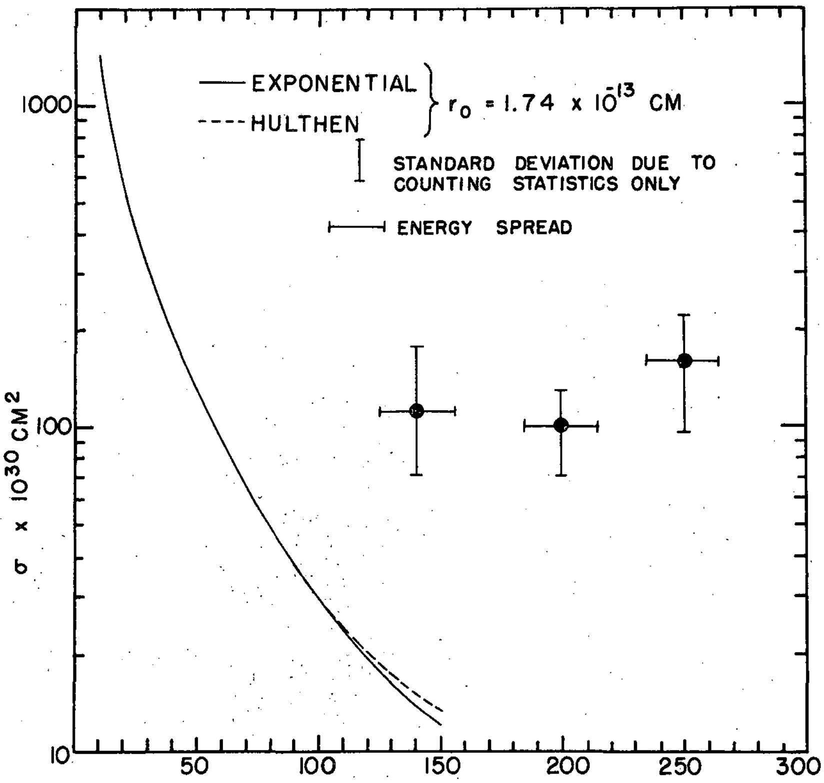

$(\frac{d\sigma}{d\Omega})_\theta$
x 10^{-29} CM^2/STERADIAN PHOTON
E_γ = 250 MEV IN C.M.
= 286 MEV IN LAB SYSTEM
3.0
2.5
2.0
1.5
1.0
0.5
0
20
40
60
80
100
120
140
160
180
$\theta_{C.M.}$
MU3674

Fig. 6


EXPONENTIAL
HULTHEN
$r_0 = 1.74 \times 10^{-13}$ CM
STANDARD DEVIATION DUE TO COUNTING STATISTICS ONLY
ENERGY SPREAD
$\sigma \times 10^{30}$ CM^2
1000
100
10
50
100
150
200
250
300

MU3673

Fig. 7