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PHOTODISINTEGRATION OF DEUTERONS AT HIGH ENERGIES

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PHOTODISINTEGRATION OF DEUTERONS AT HIGH ENERGIES*†

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ABSTRACT

Photodisintegration of deuterons has been investigated by use of the photon beam from the 342-Mev synchrotron at Berkeley. A liquid deuterium target was used. Protons were detected with a telescope consisting of either twelve or thirteen scintillation counters. The height of the pulse from one of the first counters and the number of subsequent pulses served to identify the protons and determine their energy.

Differential cross sections were determined at laboratory angles of 36°, 49°, 75°, 106°, and 141° and at energies ranging from 136 Mev to 293 Mev, and curves of the form

$$d\sigma/d\Omega' = A + B\cos\theta' + C\cos^2\theta'$$

were fitted to the experimental points at various energies. Total cross sections in the region of 70 μb were obtained.

A comparison with the results of similar experiments at other laboratories indicates that beam monitoring is within 10% agreement in absolute value between the Berkeley synchrotron and other synchrotrons.

A method is described for experimentally measuring the nuclear attenuation correction inherent in range counters, rather than calculating the correction.

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†This work was performed under the auspices of the U. S. Atomic Energy Commission.

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INTRODUCTION

When this experiment was undertaken, experimental results on deuteron photodisintegration at high energies had been published by Benedict and Woodward,[1] Kikuchi,[2] Littauer and Keck,[3] and Gilbert and Rosengren.[4] These experiments established some of the qualitative features of the process, but there were disagreements as to the angular distribution and magnitude of the total cross sections. In view of these inconsistencies in the existing data and because of the fundamental nature of the reaction, it was thought worth while to do the experiment at this laboratory using a different experimental technique.

Before this work was completed, results of high-energy experiments at California Institute of Technology, Cornell University, and University of Illinois were reported. A comparison of those results with results of this experiment is made in a later section.

EXPERIMENTAL METHOD

A diagram of the experimental arrangement is shown in Fig. 1. The photon beam was produced by the high-energy electron beam striking a 0.020-in. platinum target in the Berkeley synchrotron. The maximum electron energy in the synchrotron at the target was taken to be 342 ± 6 Mev. This is based on pair spectrometer measurements made by Anderson, Kenney, and McDonald.[5] Powell et al.[6] give the photon spectrum for a 0.020-in. platinum target. It was modified to account for the spread in the energy of the electrons as they struck the target. After suitable collimation the beam entered a liquid deuterium target which consisted of a vertical cylinder 1.5 in. in diameter with 2-mil brass walls.

Since this is a two-body reaction, measurements of the angle of emission of the proton and its energy is sufficient to determine the energy of the photon producing the event. Protons were detected with a scintillation counter telescope consisting of a series of either twelve or thirteen counters with intervening copper absorbers as indicated schematically in Fig. 2. Counter C_2 was a 0.5-in.

plastic scintillator viewed by a 5819 phototube through a light pipe. Counters C_3 through C_{13} were thin plastic disks viewed from the edge by 1P21 phototubes, with counter C_3 determining the aperture of the telescope. Coincident pulses from C_2 and C_3 triggered the sweep on an oscilloscope when a sufficiently heavily ionizing particle passed through. The circuits that provide the trigger signal have been described by Madey.[7] Pulses from all counters except C_3 were successively delayed, combined, and presented on the oscilloscope sweep by connecting the phototube collectors in series with a 50-foot length of 93-ohm cable between each collector. The oscilloscope sweeps were photographed individually and the required information was later read from the film. The height of the pulse from Counter C_2 determined the rate of energy loss of the particle, and the number of pulses from the subsequent counters determined, within limits, the range of the particle. These two pieces of information were generally sufficient to tell whether or not the particle was a proton. Once the particle was identified, the range measurement gave the energy of the proton and this, together with the angle of emission as determined by the position of the counter telescope, gave the energy of the photon producing the disintegration.

Figure 3 gives proton kinetic energies as a function of laboratory angle for various photon energies. The upper and lower curves, labeled 306 Mev and 130 Mev, respectively, indicate the extreme photon energies that were utilized in this experiment. The vertical lines indicate laboratory angles at which cross sections were measured. The spaces between iso-photon-energy lines are the energy intervals of the range counter as determined by the copper absorbers between counters, requiring a different set of absorbers to be used for each angle at which data were taken. The counter telescope can distinguish between protons and pions or muons. Deuterons from $\gamma + d \rightarrow \pi^0 + d$ do not have enough energy to enter the first range counter (C_4) of the counter telescope. Protons from $\gamma + n \rightarrow \pi^- + p$ or $\gamma + p \rightarrow \pi^0 + p$ have forward emission angles and low energies, which make their detection in appreciable numbers impossible.

Data were taken during two synchrotron runs, with a check point at 49°. In the second run the target diameter was increased from 1.5 in. to 4 in., and Counter C_1 was placed at the beginning of the telescope to identify neutral particles which might materialize in the absorber preceding C_2.

Previous to the experiment the counter telescope was operated in a low-intensity 340-Mev proton beam from the 184-in. cyclotron, and the phototube voltages were set 100 volts above the lower end of the plateau for detecting protons of this energy. During the experiment large numbers of mesons were always detected, and since many of these particles produced smaller dE/dx pulses than the highest-energy protons, this was taken as evidence that the counter was detecting the protons with high efficiency.

The total photon beam energy was measured with a Cornell-type thick-walled ionization chamber. Because of other experiments that were being done concurrently with this one, it was not always possible to have the Cornell chamber in place immediately behind the deuterium target, therefore a thin-walled pre-collimator ionization chamber was used as a secondary standard; but it was calibrated in terms of the Cornell chamber at least twice per day. At no time did the ratio of the readings obtained from the two chambers vary more than ± 4% from the mean value. Monitoring of the beam is considered in more detail in a later section.

TREATMENT OF DATA

Individual events were read from the film and plotted as shown in Fig. 4. One sees the proton points in a distribution fairly well separated from the mesons below. There were always a few points in the region between the proton line and the mesons. Many of these points were due to protons that interacted with nuclei in the range counters or in the absorbers between them. When there was any question as to where the line separating protons from mesons should be drawn, pieces of data taken under the same conditions were grouped together and histograms were drawn for the points in each range channel. Examples of such histograms are given in Fig. 5.

There was an appreciable probability that a proton in passing through the counter telescope would interact with a nucleus and be absorbed or strongly deflected. In other deuteron photodisintegration experiments where range- or energy-measuring counters have been used, the correction for this effect has been calculated on the basis of assumptions about the cross sections and angular distributions involved. Yamagata et al.[8] found that in the energy range of our experiment a maximum correction of 17.6% was obtained if the geometrical cross section was taken as the nuclear scattering cross section. To get an upper limit for the size of this correction they used the total neutron cross section which gave a maximum correction of 28.3%. Gilbert and Rosengren[4] calculated a maximum correction of 40%, using geometric nuclear area. Because of the magnitude of the effect and the uncertainties in its calculation, the correction for the counter used in our experiment was determined experimentally.

The 340-Mev proton beam from the 184-in. cyclotron was used to produce nearly monoenergetic protons by p-p scattering at various pairs of conjugate angles. To obtain information on the nuclear absorption for a given channel in the range counter and for a given set of range absorbers, the angle of the proton detector was set to select protons of the appropriate energy. The angle of another scintillation counter was set at the angle calculated for the companion proton. About 1000 counts were then taken and recorded photographically. Upon reading the film one could tell (a) how many of the protons failed to get to the range channel they should have reached, and (b) the apparent stopping-point distribution of those that fell short.

Two corrections to the number of protons in a given channel were necessary. It was necessary to add a number to account for the loss of protons that should have reached the channel and to subtract a number to account for protons that should have reached a higher channel but appeared to stop in the channel under consideration. The maximum correction obtained for any channel was 26%.

RESULTS

The differential cross section for a given laboratory angle and a given photon energy is

$$\frac{d\sigma}{d\Omega}(\theta,\ E) = \frac{(\text{protons in } \Delta E_p/\text{unit beam at angle } \theta)}{\Delta\Omega\,(\text{photons in } \Delta E_\gamma/\text{unit beam})\,(\text{target deuterons/cm}^2)} .$$

Here ΔE_γ is one of the photon spectrum intervals described in "Experimental Method." E_γ is taken as the center of this interval. ΔE_p is the proton energy interval corresponding to ΔE_γ. $\Delta\Omega$ is the proton detector solid angle.

The unit of beam was taken as that required to produce 0.1 microcoulomb of charge in the precollimation ionization chamber, which was frequently calibrated in terms of the Cornell-type thick-walled ionization chamber.

Several articles from the California Institute of Technology synchrotron group[9, 10] reported calibration of this type of chamber at 500 Mev. A value of $(4.75 \pm .13) \times 10^{18}$ Mev/coulomb was obtained by use of a pair spectrometer and a value of $(4.12 \pm .20) \times 10^{18}$ Mev/coulomb was obtained by use of the shower method of Blocker, Kenney, and Panofsky.[11] They decided to use an average value of 4.44, which they state corresponds to 3.91 at 300 Mev. They also state that the calibration at the Cornell synchrotron for this type of chamber is 3.68 at 300 Mev. The spread about their average value is ± 7%.

William Imhof at Berkeley constructed the Cornell-type thick-walled chamber and calibrated this chamber by the shower method. He obtained a number that agreed with the Cornell calibration value at that time of 3.74 (which had been transmitted via letter from R. R. Wilson to A. C. Helmholz); however, the limit of accuracy of Imhof's measurements was ~ 10%. The Cornell machine has a peak energy of 315 Mev, and at that time it was thought that the Berkeley machine had a peak energy of 322 Mev; hence, the difference in peak energies would have been negligible. Recently, however, the peak energy of the Berkeley synchrotron has been found to be 342 Mev.[5]

We used 3.74×10^{18} Mev/coulomb in our calculations. As it is now believed that the Berkeley synchrotron has a peak energy of 342 Mev, the calibration value obtained at Cornell (i.e., 3.74) should in principle be raised by ~ 2% (according to the CIT data) when it is compared with calibration measurements performed at Berkeley by Imhof. In point of fact, 2% is much less than the 10% accuracy of Imhof, and this small difference would not be evident. To further complicate the picture, the Cornell chamber that was used as a monitor in our experiment was recalibrated during the second synchrotron run, with a result of 3.34×10^{18} Mev/coulomb, a value about 11% lower than the 3.74 value. We are forced to conclude that we do not know the beam calibration to better than 10%, and have decided more or less arbitrarily to use the value of 3.74×10^{18} Mev/coulomb in reducing our data.

Correction was made for the actual temperature and pressure of the air in the chamber.

Laboratory and center-of-mass differential cross sections for various energies and angles are given in Table I. The errors quoted are standard deviations due to counting statistics. Figure 6 shows the agreement between cross sections measured at 49° in the first and second synchrotron runs. For obtaining angular distributions and total cross sections, data from Channels 1 and 2, from 3 and 4, from 5 and 6, and from 7 and 8 were combined. Curves of the form $d\sigma/d\Omega' = A + B \cos\theta' + C \cos^2\theta'$ were fitted to the experimental points at photon energies of 143, 173, 209, 253, and 293 Mev, and the ratios of the constants B and C to the constant A are plotted as a function of photon energy in Fig. 7. Integration of the angular distribution curves gives for the total cross section $\sigma_T = 4\pi (A + \frac{C}{3})$. Figure 8 shows the total cross sections as a function of energy.

Table I. Differential cross sections for photodisintegration of deuterons at various energies and angles (θ = lab.; θ' = c.m.).

θ (deg)	$\langle E_\gamma \rangle$ (Mev)	θ' (deg)	Photons in ΔE_γ per unit beam	$d\sigma/d\Omega$ (μb)	$d\sigma/d\Omega'$ (μb)
36	150	42.8	0.503×10^8	12.7 ± 0.9	9.6 ± 0.7
	165	43.2	0.490	8.8 ± 0.9	6.6 ± 0.7
	182	43.5	0.482	8.5 ± 1.1	6.3 ± 0.8
	200	43.9	0.471	6.9 ± 1.0	5.1 ± 0.8
	220	44.4	0.462	9.9 ± 1.0	7.1 ± 0.7
	242	44.8	0.454	8.6 ± 0.9	6.1 ± 0.6
	266	45.3	0.443	10.5 ± 1.0	7.4 ± 0.7
	293	45.7	0.417	8.5 ± 0.9	5.9 ± 0.6
49	136	57.3	0.518×10^8	9.7 ± 1.2	7.8 ± 0.9
(Run II)	150	57.7	0.503	10.1 ± 1.4	8.1 ± 1.1
	165	58.2	0.490	8.4 ± 1.1	6.7 ± 0.9
	182	58.6	0.482	7.9 ± 1.2	6.2 ± 0.9
	200	59.1	0.471	6.6 ± 1.2	5.2 ± 0.9
	220	59.7	0.462	8.3 ± 1.0	6.4 ± 0.8
	242	60.2	0.454	8.7 ± 1.0	6.7 ± 0.8
	266	60.8	0.443	8.0 ± 1.2	6.1 ± 0.9
	293	61.4	0.417	7.5 ± 1.2	5.8 ± 0.9
49	136	57.3	2.41×10^8	10.0 ± 1.0	8.1 ± 0.8
(Run I)	150	57.7	2.34	7.3 ± 1.0	5.8 ± 0.8
	165	58.2	2.28	8.0 ± 0.9	6.4 ± 0.7
	182	58.6	2.24	8.9 ± 0.9	7.0 ± 0.7
	200	59.1	2.19	6.5 ± 0.8	5.1 ± 0.6
	220	59.7	2.15	7.8 ± 0.9	6.1 ± 0.7
	242	60.2	2.11	8.1 ± 0.8	6.3 ± 0.6
	266	60.8	2.06	8.9 ± 0.9	6.8 ± 0.7
	293	61.4	1.94	9.2 ± 0.9	7.0 ± 0.7

Table I (continued)

θ (deg)	E_γ (Mev)	θ' (deg)	Photons in ΔE_γ per unit beam	dσ/dΩ (μb)	dσ/dΩ' (μb)
75	136	85.7	2.41×10^8	6.7 ± 0.7	6.4 ± 0.7
	150	86.2	2.34	8.0 ± 0.7	7.7 ± 0.6
	165	86.8	2.28	7.2 ± 0.7	6.9 ± 0.7
	182	87.3	2.24	6.2 ± 0.7	6.0 ± 0.7
	200	87.9	2.19	6.8 ± 0.7	6.5 ± 0.6
	220	88.6	2.15	6.2 ± 0.7	6.1 ± 0.7
	242	89.2	2.11	6.9 ± 0.7	6.7 ± 0.7
	266	89.9	2.06	7.5 ± 0.7	7.3 ± 0.7
	293	90.6	1.94	6.2 ± 0.7	6.0 ± 0.6
106	136	116.5	2.41×10^8	4.2 ± 0.6	4.9 ± 0.7
	150	117.0	2.34	3.7 ± 0.5	4.4 ± 0.6
	165	117.5	2.28	3.7 ± 0.5	4.4 ± 0.6
	182	118.1	2.24	3.3 ± 0.5	4.0 ± 0.6
	200	118.7	2.19	4.5 ± 0.5	5.5 ± 0.6
	220	119.3	2.15	4.7 ± 0.5	5.9 ± 0.6
	242	120.0	2.11	3.5 ± 0.6	4.5 ± 0.7
	266	120.7	2.06	4.8 ± 0.5	6.1 ± 0.6
	293	121.3	1.94	4.8 ± 0.5	6.2 ± 0.7
141	165	148.5	2.28×10^8	1.7 ± 0.4	2.3 ± 0.6
	182	148.8	2.24	1.8 ± 0.5	2.5 ± 0.7
	200	149.2	2.19	1.8 ± 0.4	2.5 ± 0.6
	220	149.6	2.15	2.6 ± 0.5	3.8 ± 0.7
	242	150.0	2.11	2.1 ± 0.5	3.2 ± 0.7
	266	150.4	2.06	3.1 ± 0.5	4.8 ± 0.7
	293	150.8	1.94	1.8 ± 0.5	2.8 ± 0.8

High-energy photodisintegration of deuterons has been under investigation at most laboratories where accelerators are available, and at least preliminary results on several of these experiments have been reported. For example, Keck et al.,[12] working at Cornell, measured angular distributions at photon energies of 180 and 260 Mev. They employed a counter telescope that measured dE/dx and range. Their differential cross sections are shown with some from our experiment in Figs. 9 and 10. The total cross sections are included in Fig. 8. It can be seen that the angular distributions agree fairly well, but there is a small difference in absolute values. A series of experiments at Illinois has covered the energy region from 20 to 260 Mev. Allen[13] measured cross sections from 20 to 65 Mev, using nuclear emulsions. An experiment extending into the energy region of our experiment was done by Whalin,[14] who also used nuclear emulsions. Yamagata et al.[8] used a proton counter telescope of five organic scintillators to measure cross sections at three angles and at energies from 142 to 260 Mev. Schriever et al.[15] used nuclear emulsions in an experiment extending from 70 to 235 Mev. Some of the results of the above experiments are plotted with those of our experiment in Figs. 7 and 8. No errors are available for the ratios B/A and C/A in the Illinois experiments.

At the California Institute of Technology, Tollestrup, Keck, and Smythe[16] have obtained excellent angular distributions at energies from 100 Mev to 450 Mev, using a counter telescope which measured dE/dx and range. The coefficients of the angular distributions and the total cross sections are given in Figs. 7 and 8.

From Fig. 7 it is evident that the data of all experiments in the region from 140 to 300 Mev agree in showing a decreasing value of the asymmetric $\cos\theta'$ contribution, while the symmetric $\cos^2\theta'$ term remains fairly constant, with perhaps a slight decrease indicated by the Cal Tech data.

The total cross sections obtained in our experiment are about 15% higher than the average of cross sections obtained elsewhere. The discrepancy is possibly due to the uncertainties in beam calibration discussed earlier, or to the differences between our experimentally measured corrections for nuclear attenuation and those calculated by others using estimated fractions of the total cross sections for proton removal from their counter telescopes.

Because of the familiarity of this subject, we will not discuss further the interpretation of experimental results. Reference may be made to a brief discussion by Whalin[14] of possible theoretical interpretations. Recent theoretical papers on deuteron photodisintegration have been published by Levinger,[17] Yamaguchi and Yamaguchi,[18] and others.[19,20,21]

ACKNOWLEDGMENTS

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FIGURE CAPTIONS

Fig. 1. Experimental arrangement at 75°.

Fig. 2. Electronics block diagram.

Fig. 3. Dynamics of deuteron photodisintegration.

Fig. 4. Examples of data plots.

Fig. 5. Differential pulse-height spectra in dE/dx counter for particles of defined residual range.

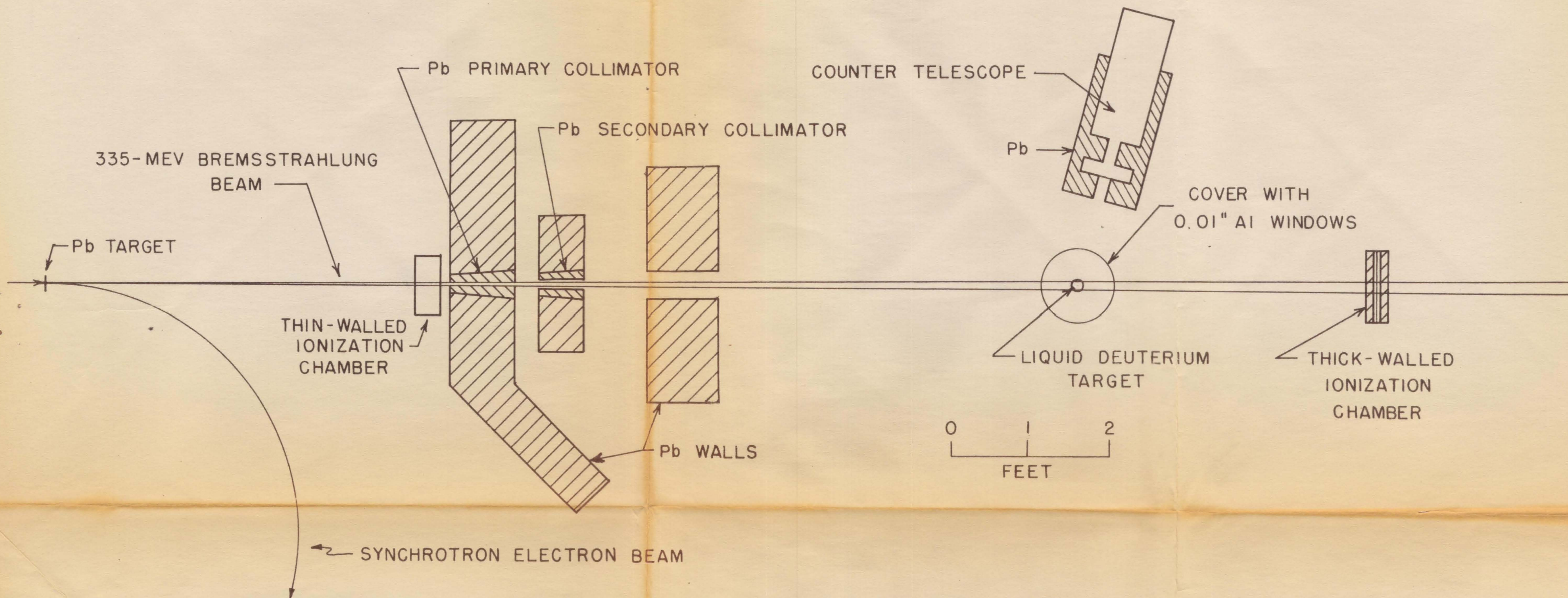
Fig. 6. Differential cross sections versus photon energy for $\theta = 49^{\circ}$.

Fig. 7. Angular distributions as functions of energy.

Fig. 8. Total cross sections as functions of energy.

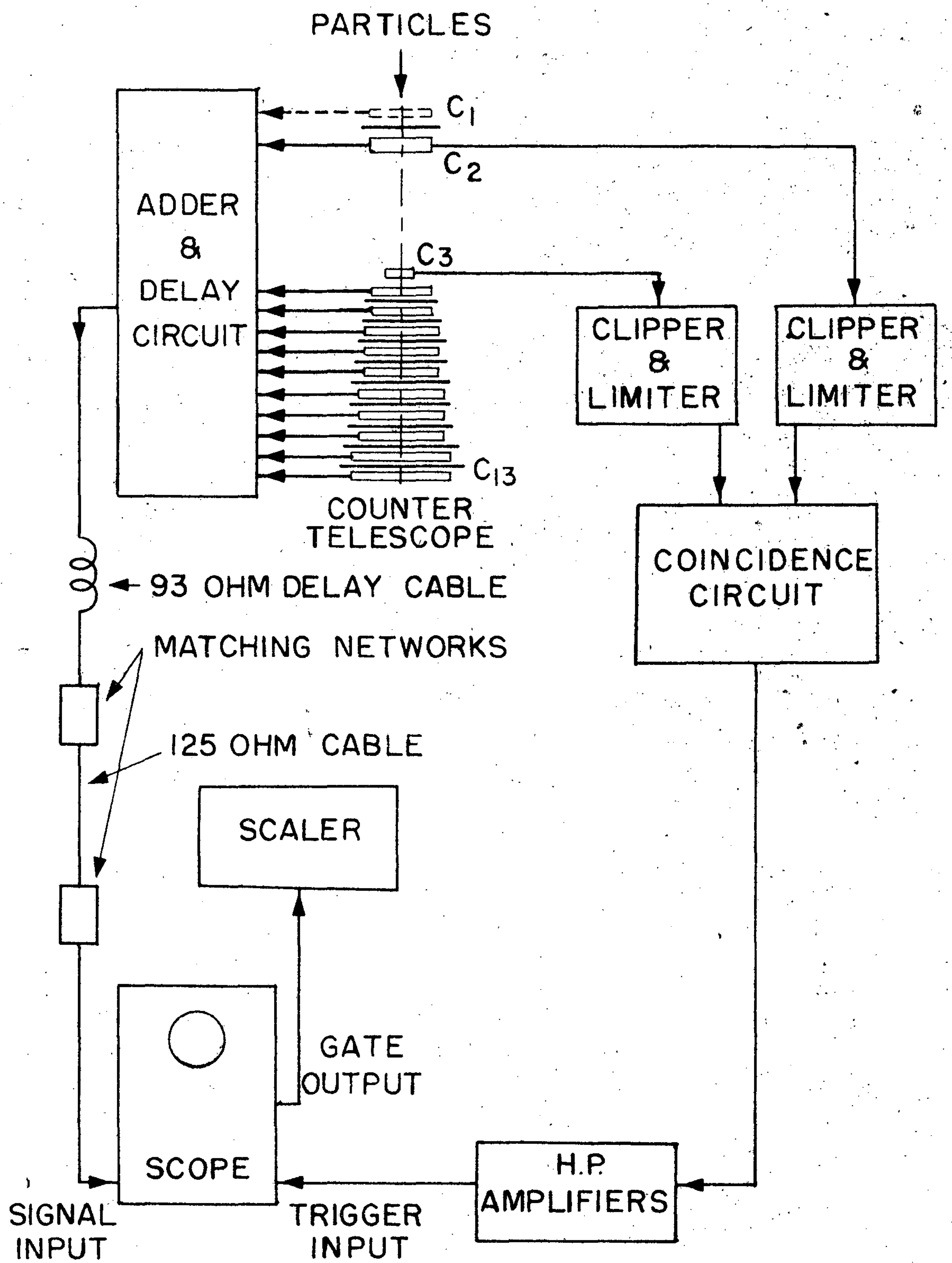
Fig. 9. Angular distribution for $E_{\gamma} = 173$ Mev.

Fig. 10. Angular distribution for $E_{\gamma} = 253$ Mev.



EXPERIMENTAL ARRANGEMENT AT 75°

23344-3 Fig. 1



ELECTRONICS BLOCK DIAGRAM

Fig. 2

23345-1

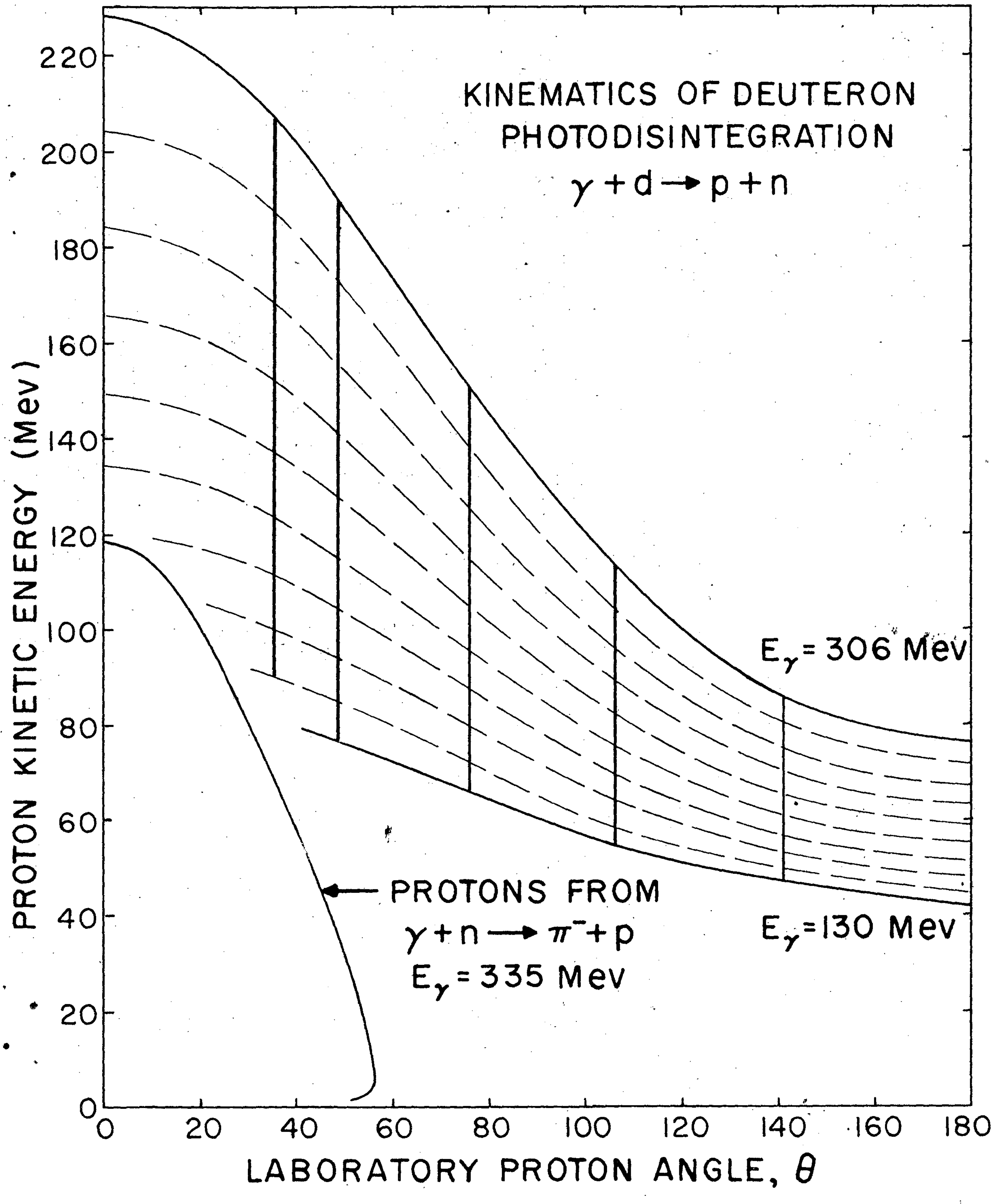

KINEMATICS OF DEUTERON PHOTODISINTEGRATION
γ + d → p + n
PROTON KINETIC ENERGY (Mev)
LABORATORY PROTON ANGLE, θ
Eγ = 306 Mev
Eγ = 130 Mev
PROTONS FROM
γ + n → π⁻ + p
Eγ = 335 Mev
0
20
40
60
80
100
120
140
160
180
200
220

Fig. 3

22968-1

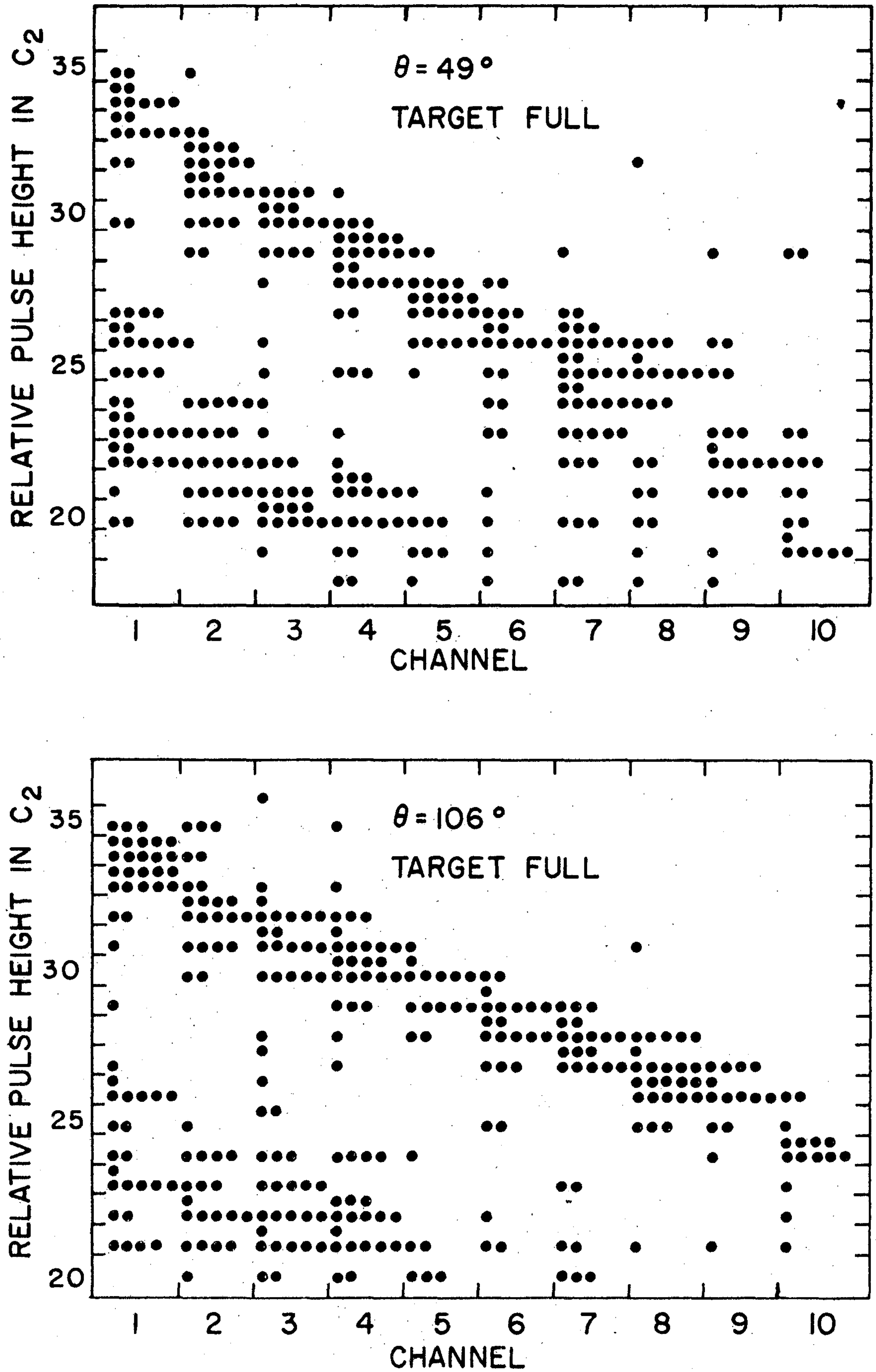
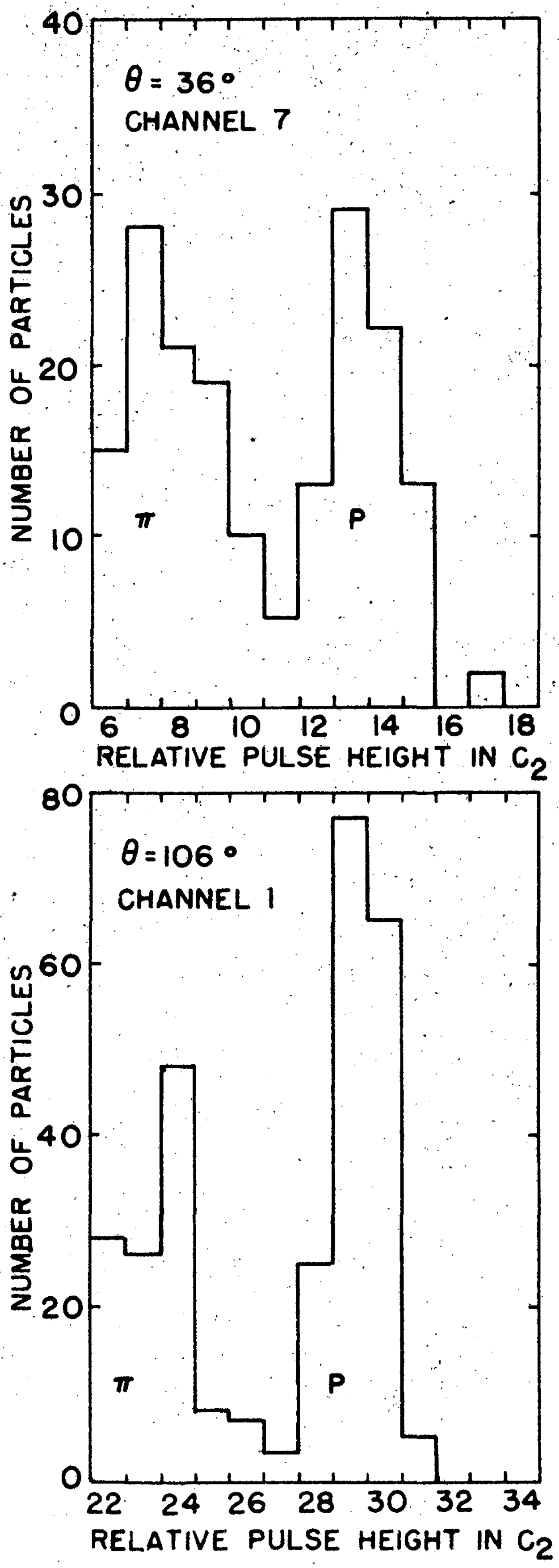

θ = 49°
TARGET FULL
RELATIVE PULSE HEIGHT IN C2
35
30
25
20
1 2 3 4 5 6 7 8 9 10
CHANNEL
θ = 106°
TARGET FULL
RELATIVE PULSE HEIGHT IN C2
35
30
25
20
1 2 3 4 5 6 7 8 9 10
CHANNEL

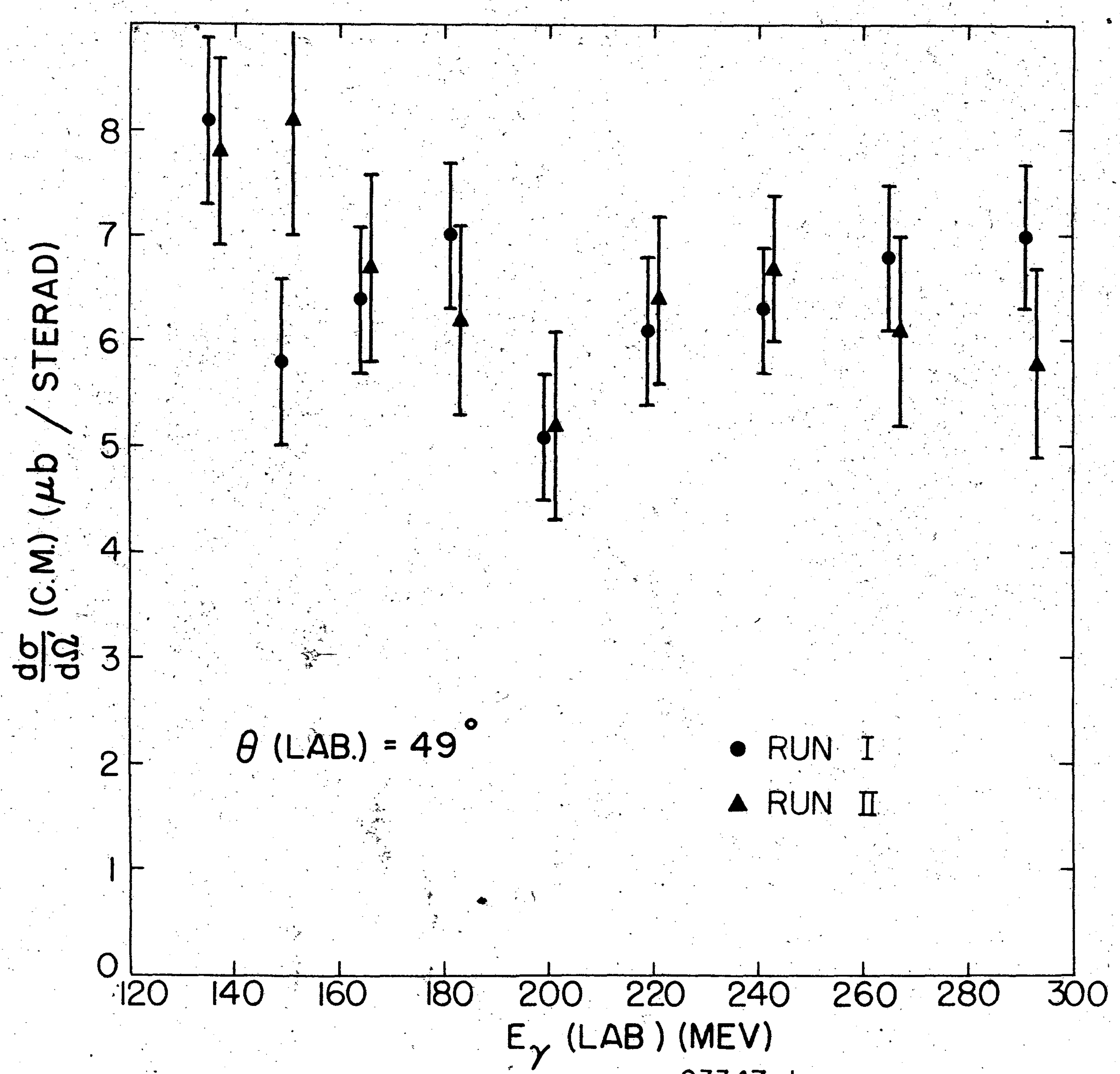
Fig 4



θ = 36°
CHANNEL 7
NUMBER OF PARTICLES
RELATIVE PULSE HEIGHT IN C2
π
P
θ = 49°
CHANNEL 4
θ = 106°
CHANNEL 1
θ = 141°
CHANNEL 4

23367-1

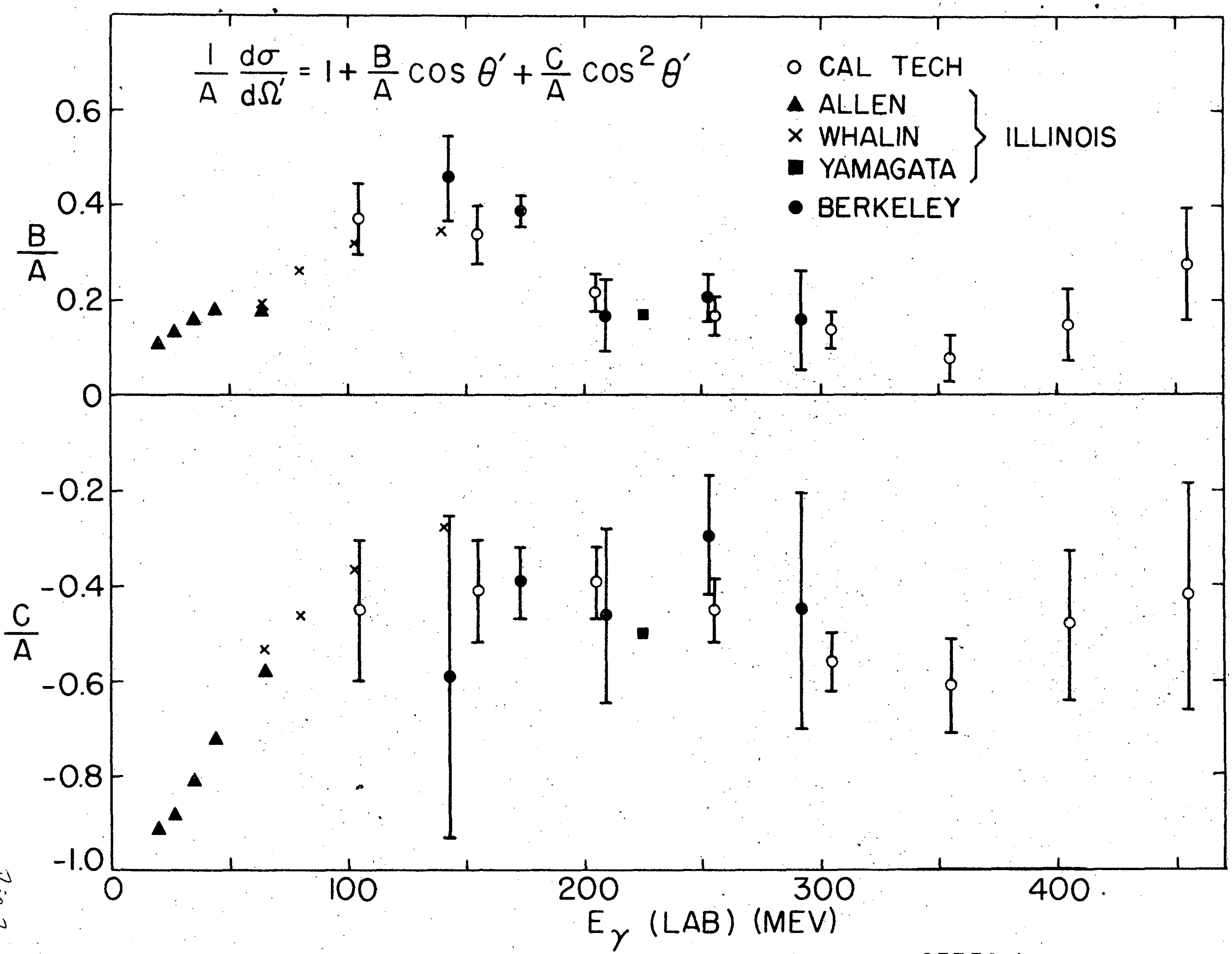
Fig. 5



dσ/dΩ (C.M.) (μb / STERAD)
8
7
6
5
4
3
2
1
0
120
140
160
180
200
220
240
260
280
300
Eγ (LAB) (MEV)
θ (LAB.) = 49°
● RUN I
▲ RUN II

23347-1

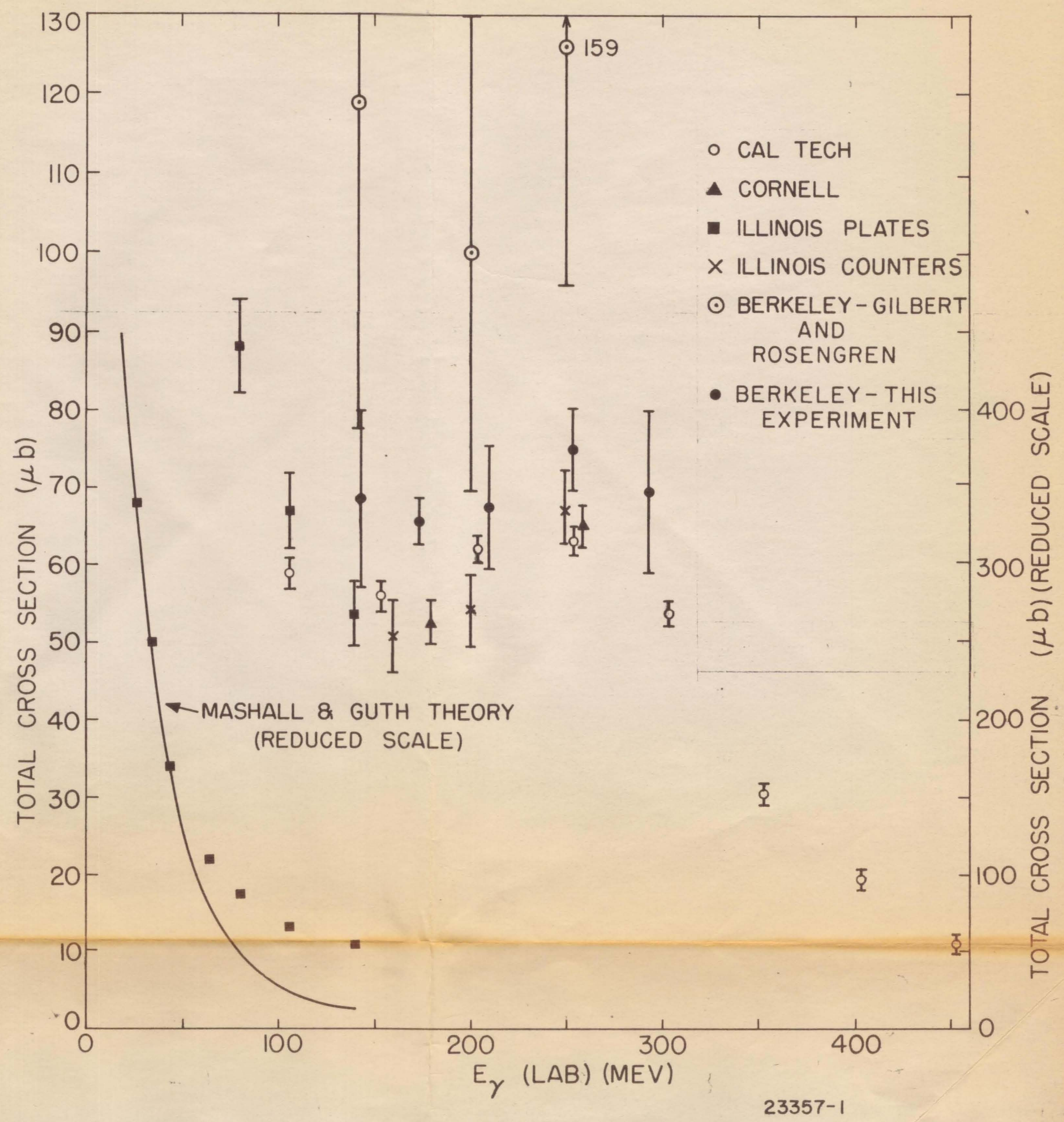
Fig. 6



$\frac{1}{A}\frac{d\sigma}{d\Omega'} = 1 + \frac{B}{A}\cos\theta' + \frac{C}{A}\cos^2\theta'$
CAL TECH
ALLEN
WHALIN
YAMAGATA
ILLINOIS
BERKELEY
B/A
C/A
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1.0
0
100
200
300
400
E_γ (LAB) (MEV)

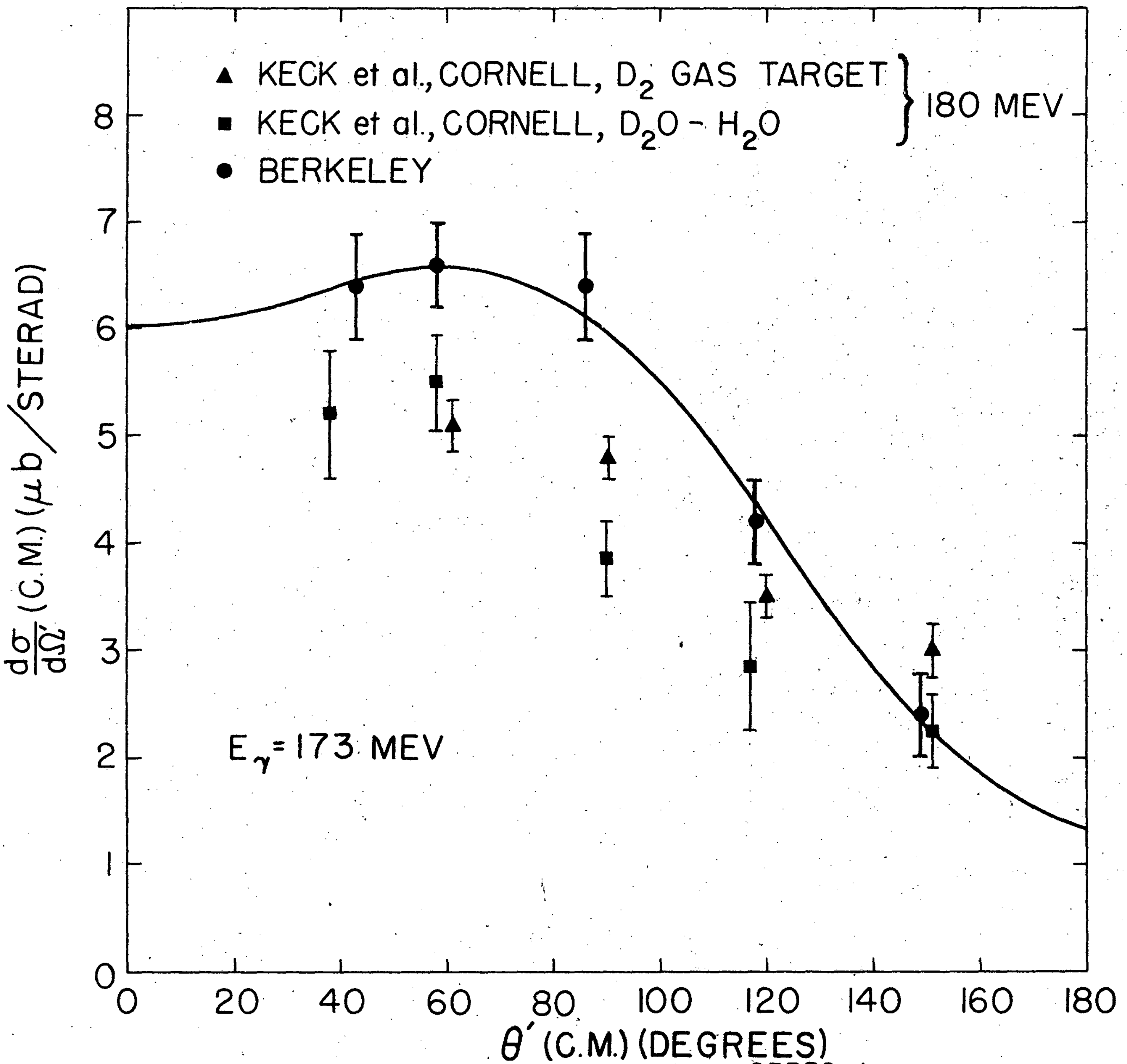
Fig. 7

23356-1



O CAL TECH
▲ CORNELL
■ ILLINOIS PLATES
× ILLINOIS COUNTERS
⊙ BERKELEY - GILBERT AND ROSENGREN
● BERKELEY - THIS EXPERIMENT
159
MASHALL & GUTH THEORY (REDUCED SCALE)
TOTAL CROSS SECTION (μb)
TOTAL CROSS SECTION (μb) (REDUCED SCALE)
Eγ (LAB) (MEV)
23357-1

Fig. 8



KECK et al., CORNELL, D2 GAS TARGET
KECK et al., CORNELL, D2O - H2O
BERKELEY
180 MEV
Eγ = 173 MEV
dσ/dΩ′ (C.M.) (μb/STERAD)
θ′ (C.M.) (DEGREES)
0 20 40 60 80 100 120 140 160 180
0 1 2 3 4 5 6 7 8

23352-1

Fig. 9

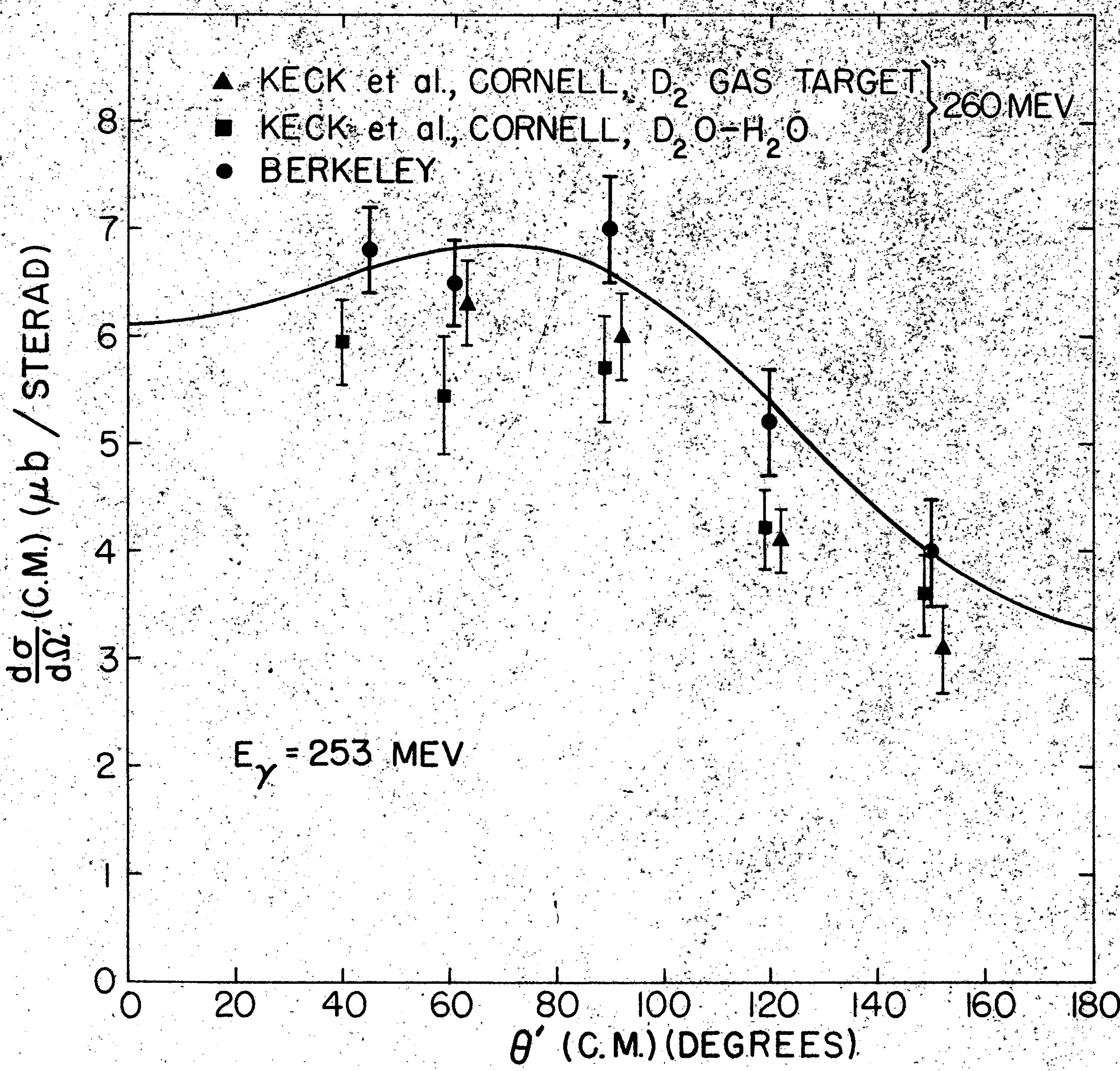


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Fig. 10