Energetic Protons from Nuclei Exposed to 300-Mev Bremsstrahlung*

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The protons ejected from various nuclei by the photon beam from the 300-Mev Cornell synchrotron have been studied with a scintillation counter telescope capable of distinguishing particles of different mass. The energy spectrum of protons from carbon and cadmium is roughly proportional to $1/E^2$ from 70 to 130 Mev and to $1/E^6$ from 130 to 240 Mev. The angular distribution of protons from carbon has a forward asymmetry which increased with proton energy. The yield per nucleus of 130-Mev protons from Be, C, Al, Cu, Cd, and Pb is proportional to Z. The excitation function for 105-Mev protons exhibits a steep rise in the neighborhood of a synchrotron energy of 200 Mev.

The experimental results indicate the majority of the protons to be of photoelectric rather than mesonic origin. There is some evidence that the recoil particle involved in the production process carries off about half the primary photon energy, which suggests that it may be a neutron.

INTRODUCTION

EARLY investigations of the secondary radiation from targets exposed to 300-Mev synchrotron photons indicated that numerous protons having energies of the order of 100 Mev were emitted at large angles to the beam. Various processes could account for the presence of a few energetic protons. However, the number observed was completely unanticipated and could not be readily explained by existing theories on the interaction of photons with nuclei. Since the identification of the particles was at best tentative in the early work, the need for better experiments was clear. It was the hope that such experiments would furnish some clues as to the mechanism of proton production and so permit a more precise evaluation of its role in the study of nuclear phenomena.

Concurrent with the investigation reported here similar studies were being carried out by other experimenters. D. Walker[1] used photographic plates to study protons generated by 195-Mev synchrotron radiation. Levinthal and Silverman[2] used proportional counters to detect protons in the energy range from 10 to 70 Mev produced by 320-Mev synchrotron radiation. A series of experiments which may well bear an important relation to the proton experiments are those on the production of photo nuclear stars by S. Kikuchi[3,4] and by R. D. Miller.[5] The energetic protons may be prongs of these stars.

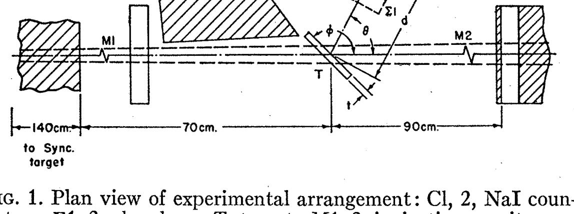

FIG. 1. Plan view of experimental arrangement: Cl, 2, NaI counters; Σ1, 2, absorbers; T, target; M1, 2, ionization monitors.

* This paper is based on a thesis submitted to the faculty of Cornell University in partial fulfillment of the requirements for the degree of Doctor of Philosophy. The work was performed in part while the author was an AEC Predoctoral Fellow and was assisted by the ONR.

1 D. Walker, Phys. Rev. **81**, 634 (1951).

2 C. Levinthal and A. Silverman, Phys. Rev. **82**, 822 (1951).

APPARATUS

A. General Description

In this experiment, various targets were exposed to the photon beam from the Cornell synchrotron and the spectrum of secondary protons having energies greater than 70 Mev was studied with a detecting telescope consisting of two NaI scintillators. A plan drawing of the experimental arrangement is shown in Fig. 1.

To make counting with a slow phosphor like NaI possible, the beam was "expanded" to approximately 2000 μsec. Since the magnetic field of the synchrotron varies sinusoidally at 30 cycles per second, the electrons producing the photons are not monochromatic but are distributed in energy from 280 to 310 Mev[6] with an average energy of about 300 Mev. The photon beam was collimated by a 2-cm hole and had a diameter of 3 cm at the position of the external targets. The integrated beam intensity for a run was measured by the charge collected in two ionization chambers: one in front of the targets, M1, and the second behind the targets, M2. The chamber associated with M2 was embedded in a block of lead at a depth of 1 cm. This located it approximately at the maximum of the transition curve for high energy bremsstrahlung and made it virtually insensitive to scattered radiation from collimator and slit systems. Absolute calibrations of the monitors were obtained by J. DeWire, who made measurements with the Cornell pair spectrometer, and by R. Littauer, who used the method of Blocker, Kenney, and Panofsky.[7] The two determinations agreed within 10 percent.

3 S. Kikuchi, Phys. Rev. **80**, 492 (1950).

4 S. Kikuchi, Phys. Rev. **81**, 1060 (1951).

5 R. D. Miller, Phys. Rev. **82**, 260 (1951).

6 J. DeWire, measurements made with Cornell pair spectrometer.

7 Blocker, Kenney, and Panofsky, Phys. Rev. **79**, 419 (1950).

A drawing of the detecting telescope is shown in Fig. 2. It employed two NaI(Tl) crystals mounted on RCA 5819 photomultipliers. The range interval in which particles were counted was defined by setting an energy bias on the rear counter, C2. A differential discriminator was used to obtain the pulse-height distribution for the front counter, C1, in coincidence with the rear counter. Peaks corresponding to particles of different mass were easily distinguished: mesons, protons, and deuterons of the same residual range have specific ionizations in the ratio of 0.4:1:1.3 respectively. The total weight of material in front of the rear counter determined the minimum range of a particle which could be detected. For mesons, protons, and deuterons this range corresponded to energies of 25, 55, and 70 Mev. The system was essentially self-calibrating. A rough preliminary comparison with the pulses produced by 2.6-Mev thorium γ-rays enabled one to identify the peaks corresponding to different particles. Once this identification was made, a very accurate calibration could be obtained from the known range-energy relations.[8,9]

The recording electronic equipment was of standard design. The amplifiers had an over-all gain of 40 and a rise time of about 0.1 μsec. Coincidence gates were delay-line formed and of 1 μsec duration. The system was clamped except for a 3 millisec interval bracketing the beam pulse. The data recorded were (1) the singles rate for each counter, (2) the coincidence rate, (3) the delayed coincidence (accidental) rate, (4) the pulse-height distribution in either counter, alone or in coincidence with the other.

The most serious limitation on the precision of the experiment arose from the stability required in the high voltage set for the photomultipliers. The reason for this is that the range interval defined by the rear counter and hence the counting rate of the detector is extremely sensitive to the gain of the multipliers. In particular, if we wish to obtain 10 percent stability in the counting rate, the high voltage must be stable to 0.5 percent. Even though the high voltage was battery-regulated, fluctuations of this magnitude could occur under adverse conditions and, for this reason, counting was in general limited to 10 percent statistical accuracy and runs were repeated at least twice.

B. Response Curves for the Counters

Figure 3 shows a typical number-bias curve for the rear counter. The run was taken with the front counter biased to count any particle losing more than 0.7 the energy lost by a fast electron traversing the counter, ~3.3 Mev. The solid curve is the response expected assuming that the particles are protons and that the counting rate is proportional to the range interval defined by a given bias setting. The dashed curve takes into account the proton spectrum and the finite resolution of the counter (estimated at 10 percent). Fitting the curves to the data gives an accurate point on the calibration curve corresponding to the energy lost by a proton of range equal to the thickness of the crystal.† Using this calibration point we have calculated the pulse height corresponding to a minimum ionizing proton. The value is indicated on the abscissa along with the observed electron pulse height. The counting arrangement used in this measurement did not discriminate against deuterons or π^- mesons which produce

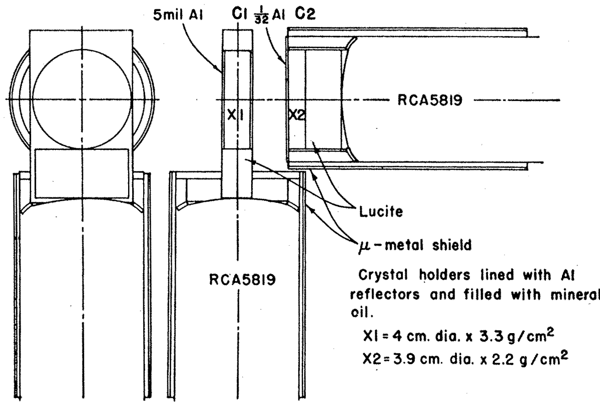

FIG. 2. Detail of counter telescope.

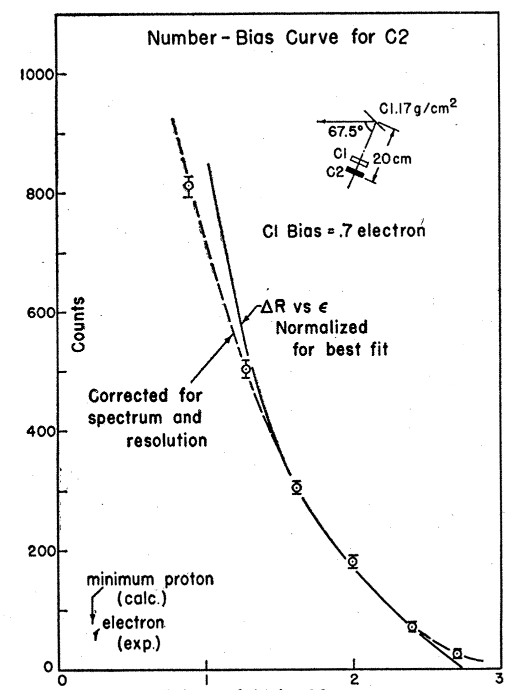

FIG. 3. Integral number-bias curve for rear counter in coincidence with front counter. See Sec. IIB for explanation of curves.

† Throughout this paper, ranges are given in g/cm² NaI equivalent. The stopping power of NaI relative to aluminum was taken as 0.75.

[8] R. R. Wilson, private communication. Cornell range-energy nomograph.

[9] C. J. Bakker and E. Segrè, Phys. Rev. 81, 489 (1951).

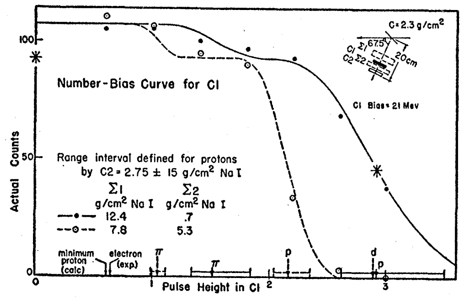

FIG. 4. Integral number-bias curves for front counter in coincidence with rear counter. See Sec. IIB for explanation of curves.

stars. The good fit of the theoretical curve is some evidence that these particles must be present only in relatively small numbers.

Typical number-bias curves for the front counter are shown in Fig. 4. The two distributions correspond to different residual ranges defined by the rear counter. The curves indicate the expected pulse-height distribution corrected for resolution and energy straggling. They were normalized to fit the experimental data at the points indicated by stars. It should be pointed out that these two points fix the "proton part" of both curves since the relative position of the curves is determined by the range energy relation. There is some indication of the presence of mesons but the statistics are too poor in these data to be convincing. Other data show the meson peak well resolved and it is from these statistically better measurements that the ratio of mesons to protons indicated by the curves was obtained. The arrows along the abscissa indicate the expected locations of the half value points. The brackets around

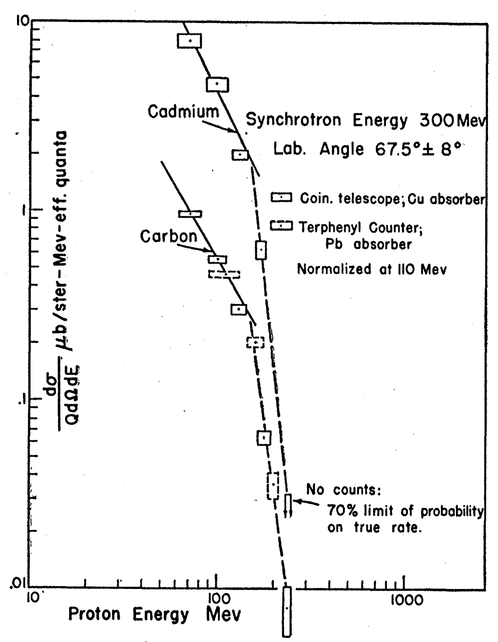

FIG. 5. Differential energy spectra of protons at 67.5° produced by 300-Mev synchrotron photons on carbon and cadmium.

the arrows show the energy spread due only to the finite range interval in which the particles could stop. It should be pointed out that deuterons could have been quite easily resolved had they been present with a frequency greater than about 10 percent of the proton frequency. Also indicated on the abscissa are the expected pulse height due to a minimum proton and the observed electron pulse height.

PROTON EXPERIMENTS

A. Energy Spectrum

The differential range spectrum for protons emitted at 67.5° from carbon and cadmium targets was obtained by measuring their absorption in copper ($\Sigma 1$, in Fig. 1). The target angle, ϕ, was 135°. The distance, d, from the targets to the rear counter was 20 cm, giving an angular aperture of $\pm 6°$. The sensitive range interval defined by the rear counter was 2.8 g/cm² NaI. The target thickness was increased with increasing range in order to keep up the counting rate. Runs with different target thickness were overlapped to check that the number of protons was proportional to the target thickness. Backgrounds without targets were negligible in all cases; in general there were no counts recorded at all.

The differential energy spectrum was obtained from the differential range spectrum by dividing by the value of dE/dR appropriate for the mean range. The results are plotted in Fig. 5 as a function of the energy corresponding to the mean range. The height of the rectangle around the experimental points gives the statistical error and the width gives the total energy spread due to energy loss in the target and the finite range interval in which the particles were stopped. The maximum likely error in the measurement of the absolute cross section is ± 25 percent.

The part of the data labeled "Terphenyl counter Pb absorber" was obtained as a by-product of an experiment designed to detect fast neutrons. Only the equivalent of the rear counter was used so that the discrimination against particles other than protons was not as good as for the coincidence data.

A number of corrections have been investigated. These include: (1) corrections necessary for finite energy resolution and energy loss in the targets; (2) distortion of the range spectrum due to the finite angular aperture; (3) loss of particles and distortions due to multiple Coulomb scattering; (4) effects of range and energy straggling; (5) loss of particles due to nuclear absorption and scattering. Only the last correction is appreciable. In this case it is a reasonable approximation to assume that all particles which suffer a nuclear encounter are lost. For proton energies less than 150 Mev even this correction is small. At energies greater than 150 Mev, the correction changes the slopes of the curves in Fig. 5 from -7 to -6 for carbon and from -9 to -7 for cadmium.

B. Angular Dependence

The angular distribution for protons from carbon for energies of 100, 130, and 175 Mev is shown in Fig. 6. The curves are normalized to unity at 67.5°. For angles <90°, the target angle (ϕ in Fig. 1) was 135°; for angles >90°, the target angle was 45°. The distance, d, from the target to the counter was increased to obtain better angular resolution as the angle between the beam and the counters was decreased. The height of the rectangle in Fig. 6 gives the statistical error and the width gives the total angular aperture including finite extension of the target.

An angular distribution was also attempted for cadmium. Unfortunately, a large background of scattered electrons was encountered in the forward direction which severely limited the experiment. The data are sufficient to show that the distribution for cadmium is similar to that for carbon.

In so far as the relative values of the yield are concerned, there is only one correction that might be made. This arises because protons emitted at different angles suffer a different energy loss in the target so that their mean energy varies slightly with angle of observation. The maximum error occurs at 90° where it amounts to −2 percent in the energy.

TABLE I. Total cross sections relative to 4π times differential cross sections at 67.5°.

Proton energy E Mev	$\frac{d\sigma(E)}{dE} \Big/ 4\pi\frac{d\sigma(E,\,67.5°)}{dEd\Omega}$
100	0.65 ± 0.07
130	0.69 ± 0.07
175	0.88 ± 0.09

C. Total Cross Sections

The angular distributions for carbon have been plotted as a function of $\cos\theta$ and integrated graphically to obtain total cross sections at 100, 130, and 175 Mev. The results are given in Table I. It can be seen that the total cross section is nearly proportional to the differential cross section at 67.5°, so that the differential energy spectrum given in Fig. 5 also represents reasonably well the variation of the total cross section with energy.

D. Z-Dependence

The proton yield per nucleus for various targets was measured and is plotted as a function of Z in Fig. 7. The target thicknesses were chosen to have approximately equal stopping power for protons. A correction was made for absorption of the synchrotron beam in the heavy targets. This amounted to about +20 percent for cadmium and lead and +10 percent for copper. In making the correction it was assumed that if a photon interacted at all it was effectively removed from the beam as far as the production of 130-Mev protons was concerned.

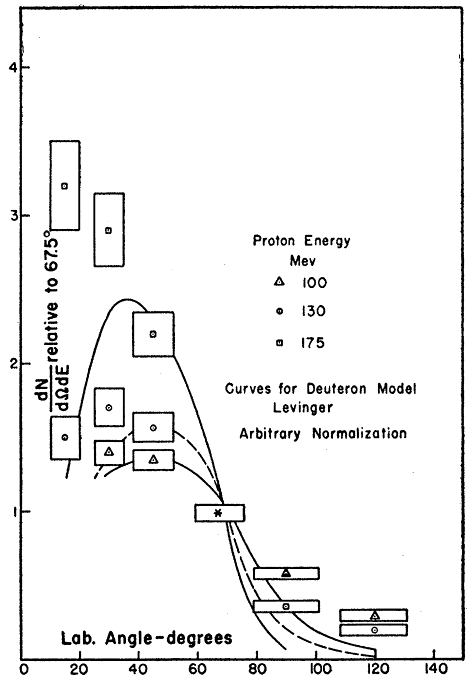

FIG. 6. Angular distributions for protons produced by 300-Mev synchrotron photons on carbon.

E. Excitation Function

An excitation function for the production in carbon of 105-Mev protons at 90° is shown in Fig. 8. Three different experiments are represented. The measurements of Stearns, Wilson, and Keck[10] were made using a single NaI counter as a detector and gave only

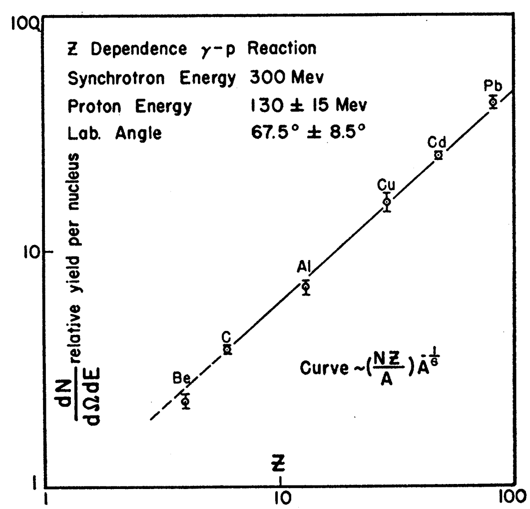

FIG. 7. Relative yield per nucleus of protons at 67.5° produced by 300-Mev synchrotron photons.

[10] Stearns, Wilson, and Keck (unpublished).

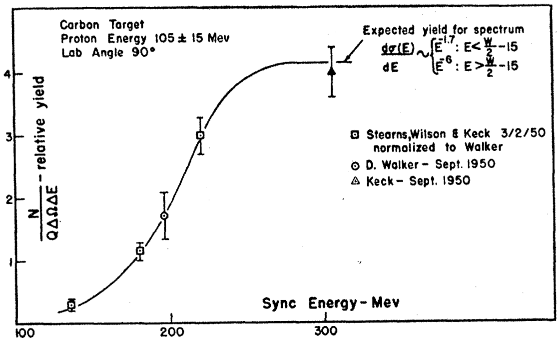

FIG. 8. Relative yield of 105-Mev protons at 90° from carbon as a function of synchrotron energy.

relative values for the proton intensity. The measurements of Walker,[1] made with photographic plates as detectors, were used to normalize the data of Stearns, Wilson, and Keck. The value of Walker's points relative to the author's should be reliable within the statistical error since Walker used the same monitors that were employed in the present experiment.

HIGH ENERGY NEUTRONS

Since the existence of high energy neutrons follows almost as a corollary from the existence of high energy protons, a preliminary search for such neutrons was made. The neutron counter consisted of a liquid scintillator (employing terphenyl dissolved in xylene) surrounded by a 2-inch thick lead shield. The neutrons were identified by observing their characteristic absorption in lead. Preliminary data so far obtained indicate equality of the high energy neutron and proton fluxes with an uncertainty of a factor two.

DISCUSSION OF RESULTS

A. Energy Spectrum

With the exception of a discrepancy in the magnitude of the absolute cross section (Table II, subsequently), the data of Fig. 5 join smoothly those of Levinthal and Silverman.[2] In the energy range from ~10 to 70 Mev they found a differential energy spectrum which was represented very well by an expression of the form,

$$d\sigma(E) \sim E^{-\gamma} dE,$$

where γ increases with atomic number from 1.7 for carbon to 2.2 for lead. The solid curves in Fig. 5 are an extrapolation of this spectrum normalized to give the best fit to the low energy points. The data fit nicely out to 130 Mev. Above this energy there is a "break" in the spectrum and the number of protons starts to decrease much more rapidly (approximately as the -6 power for carbon and the -7 power for cadmium if the correction for nuclear absorption is made). The slight increase in the exponents with increasing atomic number can be associated with inelastic scattering of the escaping protons in the nucleus and probably does not indicate a change in the production spectrum. Extrapolation to zero scattering would indicate a production spectrum falling off just slightly less rapidly than that observed for carbon.

It is of interest to compare the proton spectrum produced by 300-Mev bremsstrahlung with that obtained by Walker[1] for 195-Mev bremsstrahlung. Walker's observations show an integral spectrum falling off as the -4 power of the proton energy in the energy range 50–125 Mev. Unfortunately the statistics are not sufficiently good to enable one to deduce an accurate differential spectrum, but the measurements would certainly be consistent with a differential spectrum similar to that observed at higher synchrotron energy with the "break" occurring at 80–90 Mev.

The occurrence of a "break" in the energy spectrum at about half the maximum photon energy, W, suggests that the recoil particle involved in the production of protons by photons is a single nucleon (deuteron model). If we imagined that the recoil were a three-nucleon system (as one might expect on a strict α-particle model), the "break" should occur at about $\frac{3}{4}W$, while the recoil of a two-nucleon system would put the "break" at $\frac{2}{3}W$. The existence of a high energy tail above $\frac{1}{2}W$ leaves some ambiguity about the process. However, Levinger[11] has shown that for a "deuteron model" this tail may be completely explained by motion of two-nucleon systems in the nucleus and that one need not invoke any other processes.

B. Angular Distribution

The angular distribution (Fig. 6) shows a strong forward asymmetry which increases with increasing proton energy. This behavior extrapolates smoothly from the data of Levinthal and Silverman. At 10 Mev they found an angular distribution which was isotropic, while at 40 Mev the distribution already showed a fairly strong forward asymmetry.

A comparison of the angular distribution obtained by Walker for 90-Mev protons with that found in the present experiment for 100-Mev protons shows good agreement for both the shape of the distribution and the magnitude of the cross section. (See Table II.) This similarity in the angular distributions of protons of roughly the same energy produced by a bremsstrahlung spectrum having end-point energies of 195 and of 300 Mev indicates that there is little additional production of these protons by photons in the energy range from 195 to 300 Mev. This is consistent with the assumption of a direct photonuclear interaction. It is inconsistent with most processes involving meson production since the region of photon energies from 195 to 300 Mev should be just that which would contribute most strongly to the proton production in this case.

The strong forward asymmetry in the angular distribution also favors a direct photonuclear process. Proton

[11] J. S. Levinger, Phys. Rev. 84, 43 (1951).

recoils from meson production would have a forward asymmetry but this process can be ruled out for high energy protons by energy considerations. The process involving the production and reabsorption of a meson in the same nucleus would probably give nearly isotropic proton production.

D. *Z*-Dependence

Perhaps the one slightly surprising thing about the *Z*-dependence (Fig. 7) is that it should be so nearly proportional to the atomic number. At first thought one would expect a strict *Z*- or *A*-dependence to be modulated by a factor $A^{-1/3}$. However, an investigation of this point, which includes the effects of protons scattered into a given energy interval from a higher energy, shows that the modulation should be more nearly proportional to $A^{-1/6}$. Assuming this modulation the data are fit nicely by a primary yield which varies as $(A-Z)Z/A$. This is the variation given by Levinger and Bethe[12] for the nuclear photoeffect.

Levinthal and Silverman obtained the same *Z*-dependence for 40-Mev protons as we obtained for 130-Mev protons.

D. Excitation Function

The excitation function for 105-Mev protons is shown in Fig. 8. To test the internal consistency of the assumption of a "break" in the energy spectrum at about half the maximum photon energy, an expected yield curve was calculated for the spectrum,

$$\frac{d\sigma(E)}{dE}\sim\begin{cases}E^{-1.7}: E<\frac{1}{2}W-15\\ E^{-6}\ \ : E>\frac{1}{2}W-15\end{cases}$$

where W is the maximum photon energy and an average binding energy of 15 Mev is assumed for the protons. The curve in Fig. 8 represents the result of this calculation. It was normalized to Walker's point. It should be pointed out that a variation of ± 15 Mev in $\frac{1}{2}W-15$ or of ± 1 in the exponent of E for $E>\frac{1}{2}W-15$ begins to destroy the fit rather badly. The fit is relatively insensitive to small changes in the exponent of E for $E<\frac{1}{2}W-15$.

As can be seen, the excitation function lends support to the assumption that the proton receives about half the primary photon energy. It may also be compatible with the process involving the production and reabsorption of a meson in the same nucleus, but it is definitely incompatible with any process involving the production of both a meson and a fast proton.

E. Absolute Cross Section

As has already been mentioned there is some discrepancy in the measurement of the absolute cross section made by different experimenters. The values obtained for 70 Mev protons at 90° to the beam are compared in Table II.

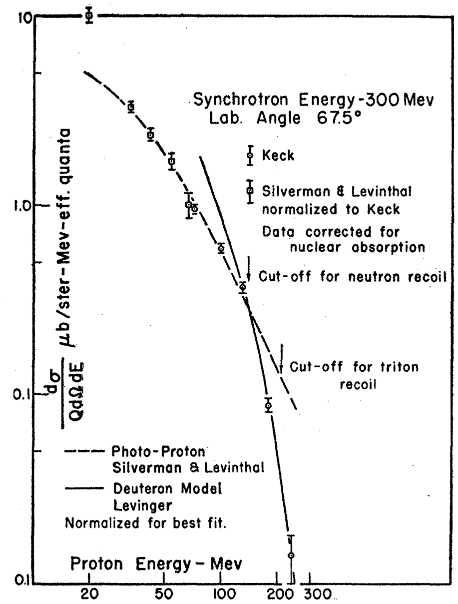

FIG. 9. Comparison of theoretical and experimental proton energy distributions.

CONCLUSIONS

As has been indicated in the previous section, a nuclear photoeffect offers a qualitatively reasonable explanation for the majority of the high energy proton production. The energy spectrum and the excitation function give some evidence that the recoiling particle or particles carry off about half the primary photon energy. The forward asymmetry in the angular distribution rather favors a strong interaction with a small subunit in the nucleus, since it would be difficult to impart sufficient forward momentum to a heavy system to produce such an asymmetry unless the distribution in the c.m. system were strongly forward.

Some preliminary theoretical calculations of the photonuclear effect have been made by Levinthal and Silverman,[2] who investigated a "one-nucleon model" of the process, and by Levinger,[11] who investigated a "deuteron model." Both theories give the correct

TABLE II. Comparison of experimental cross sections for 70 Mev protons at 90°.

	Method	Synchrotron energy Mev	μb/Mev-sterad-eff. quanta	Maximum likely error
Silverman and Levinthal	Proportional counter	300	0.15	factor 2
Walker	Photographic plates	200	0.95[a]	±55%
Keck	Scintillation counter	300	0.74	±30%

[a] The value given here is lower than that previously reported by Walker. The change is associated with improved measurements of the absolute beam intensity.

[12] J. S. Levinger and H. A. Bethe, Phys. Rev. 78, 115 (1950).

magnitude for the proton cross section at 70 Mev. Qualitatively, the "deuteron model" offers a nice explanation of the experimental indication that the proton receives about half the primary photon energy and of the forward assymmetry in the angular distribution. However, as can be seen in Figs. 6 and 9, the quantitative fit with the data is not good. On the other hand, the "one-nucleon model" fails, even qualitatively, to predict a "cutoff" in the energy spectrum but does give quite a reasonable fit to the data up to the "cutoff." (See Fig. 9.) In computing cross sections for their "one-nucleon model" Levinthal and Silverman used the nuclear momentum distribution given by Chew and Goldberger.[13] It is possible that this distribution incorporated into the "deuteron model" would give results in reasonable agreement with the experiments.

Processes involving mesonic interactions have been proposed as the explanation of photonuclear stars by Kikuchi[4] and Miller.[5] Some, and possibly all, of the protons observed in the present experiment must be prongs of these stars. While it is somewhat difficult to explain the angular distribution and the excitation function of the protons with meson models, the possibility that the protons may, at least in part, be associated with mesonic processes cannot be ruled out.‡

The author wishes to express his appreciation to Professor R. R. Wilson for his personal direction of this work. He is greatly indebted to Professor H. A. Bethe and to Doctors A. Silverman, J. S. Levinger, D. Walker, and S. Kikuchi for helpful discussions and communication of results. The assistance and cooperation of the many students and staff members who operated the synchrotron are gratefully acknowledged.

[13] G. F. Chew and M. L. Goldberger, Phys. Rev. 77, 470 (1950).

‡ It has been suggested by R. R. Wilson that the process of proton production may involve the production and subsequent reabsorption of a meson in a deuteron-like subunit inside the nucleus. In this process momentum and energy are conserved between the incident photon and the emitted proton and neutron. Such a process could give results similar to those of Levinger's deuteron model and provide a qualitatively satisfactory explanation of the observations.

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Proton-Proton Scattering at 240 Mev*

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Differential proton-proton scattering cross sections have been measured at six angles in the range from 27 to 90 degrees center of mass. The internal undeflected cyclotron beam was used with a hydrocarbon target. Proton-proton scattering was differentiated by detecting the emitted proton pair with its definite angle between particles in coincidence with two scintillation counters. Scintillator dimensions determined the solid angle accepted. The incident beam was monitored by measurement of the beta-activity induced by the reaction $C^{12}(p,pn)C^{11}$ in the target. General cyclotron background was negligible.

The cross sections measured show isotropy in the center-of-mass system within estimated errors. The average value of the cross section was 4.97 ± 0.43 millibarns/steradian based on a 49 ± 3 millibarn carbon cross section. This is in poor agreement with previous measurements of 3.6 ± 0.3 mb/steradian.

INTRODUCTION

This article describes an experimental method for measuring proton-proton scattering using the internal beam of the Rochester synchrocyclotron and presents experimental results obtained with 240-Mev protons. Preliminary reports of this work have been presented.[1] Differential cross sections have been measured at six angles in the range from 27 to 90 degrees, center of mass, obtaining an angular distribution and an absolute measure of the differential cross section.

Other proton-proton scattering results have been reported in the high energy range by Chamberlain, Segrè, and Wiegand,[2] who have made extensive measurements at 345 Mev and measurements at several angles at 249, 164, and 119 Mev. Birge, Kruse, and Ramsey,[3] using a method similar to that described here, reported measurements at 105 and 75 Mev. All measurements have shown the same general results: a center-of-mass cross section virtually independent of angle and energy.

APPARATUS AND PROCEDURE

General Description

The single dee construction of the cyclotron provided space within the tank for experimental equipment. A solid hydrocarbon target was used and the proton-proton scattering was differentiated by the method of Wilson and Creutz[4] in which counters in coincidence record the recoil and incident proton pair which

* This work has been supported by the ONR and AEC.
† Now at Brookhaven National Laboratory, Upton, New York.
[1] C. L. Oxley, Phys. Rev. 76, 461 (1949); Oxley, Schamberger, and Towler, Phys. Rev. 82, 295 (1951).
[2] O. Chamberlain and C. Wiegand, Phys. Rev. 79, 81 (1950); Chamberlain, Segrè, and Wiegand, Phys. Rev. 81, 2841 (1951); Phys. Rev. 83, 923 (1951).
[3] Birge, Kruse, and Ramsey, Phys. Rev. 83, 274 (1951).
[4] R. R. Wilson and E. C. Creutz, Phys. Rev. 71, 339 (1947).