The Production of Protons from Carbon by Monoenergetic Gamma Rays*

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A technique is described for selecting from the interactions produced by a bremsstrahlung spectrum only those arising from essentially monoenergetic quanta. These interactions are selected by requiring a coincidence with the degraded electron which produced the interacting quanta.

A study of the photoproduction of protons from carbon was made using 190-Mev monochromatic quanta from the 310-Mev Cornell synchrotron. An energy distribution of the emitted protons was observed at 60 degrees and an angular distribution of 70-Mev protons was also obtained. Interpretation of these results in terms of a deuteron model gives satisfactory agreement and indicates that the photoproduction process involves only a few nucleons on the average and probably involves just two nucleons a large fraction of the time. Rough quantitative agreement is obtained with experiments on the photodisintegration of the deuteron.

INTRODUCTION

THE study of photoproton production from nuclei containing more than two nucleons is hampered by the fact that gamma-ray sources are not capable of producing line spectra at high energies. Because of this, and because of the many particles in the nucleus, the measurement of the energy and angle of the energent proton is not sufficient to determine the parameters of the photodisintegration process. Analysis of the results of conventional experiments must include an integration over the bremsstrahlung spectrum and direct physical interpretation becomes difficult.

Photoproduction of protons from carbon has been studied by a number of experimenters.[1–6] Of the light elements carbon has been chosen as a target material for a number of practical considerations including density and convenience of preparation. While the results of these experiments are in general agreement with each other, theoretical interpretation has not been particularly successful. Levinthal and Silverman[1] assumed that the process was essentially a photoelectric process with the entire nucleus taking up the recoil of the emitted proton. This calculation gave reasonable agreement with the low-energy region of their energy spectrum but did not explain the features of the spectrum which occurred in the high proton-energy region. Levinger[7] proposed a deuteron model in which the participating nucleons were only two in number. Rather poor agreement with experiment was obtained by this calculation, due in part to the use of the simple, low-energy (below 140 Mev) theoretical results for the photodisintegration of the deuteron. Because of the integration over the bremsstrahlung spectrum it was not easy to adjust the theory in the light of newer experimental results. Yoshida[8] has made a calculation of the photoproduction process using a model in which the number of particles available to take up the recoil is left as an adjustable constant. These results do not include any mesonic effects, and the absolute cross sections obtained are much too low at the energies under consideration. Some reasonable results for angular distributions of the photoprotons were obtained, but it is not possible to conclude that the calculation is either right or wrong from this evidence alone. Yoshida does not compute an energy distribution to be expected for the protons.

The simplification in interpretation that would result from the study of photoprotons produced by an essentially monochromatic source of quanta has recently led to an effort at this laboratory in the direction of achieving experimental situations in which results from gamma rays of a narrow energy interval could be obtained. Keck and Perry[5] have studied photoprotons from carbon using the conventional subtraction technique with various synchrotron energies. However, it was felt desirable to be able to perform the experiment using a different method in order to check the results obtained by this difference technique and in order to attempt to discover a more direct approach (and perhaps a less tedious approach) to the study of photoproduction processes using essentially monoenergetic quanta for the incident spectrum.

THE MONOCHROMATIC GAMMA-RAY PRINCIPLE

The technique for selecting individual monoenergetic gamma rays which has been used in this work was originally suggested independently by Koch at Illinois and by Camac at Cornell. Maximum energy electrons circulating in the donut of the synchrotron are allowed to spiral in and strike a thin target. Some of these electrons radiate in the target and emerge from the

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1 C. Levinthal and A. Silverman, Phys. Rev. **82**, 822 (1951).
2 J. C. Keck, Phys. Rev. **85**, 410 (1952).
3 J. W. Rosengren and J. M. Dudley, University of California Radiation Laboratory Report UCRL-1913, revised (unpublished).
4 Wattenberg, Feld, and Godbole, Phys. Rev. **90**, 380 (1953).
5 J. C. Keck and A. M. Perry (private communication); also Phys. Rev. **86**, 629 (1952).
6 D. Walker, Phys. Rev. **81**, 634 (1951).
7 J. S. Levinger, Phys. Rev. **84**, 43 (1951).
8 S. Yoshida, Prog. Theoret. Phys. **6**, 1032 (1951).

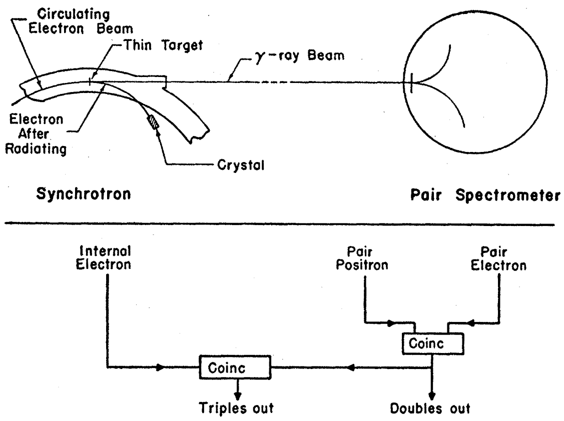

FIG. 1. Experimental arrangement for the measurement of the resolution of the monochromatic gamma-ray line.

target correspondingly degraded in energy. Because of the high energies involved the degraded electrons will emerge from the target essentially in the forward direction. Furthermore, although a nuclear field must take part in the bremsstrahlung process, it does not carry off an appreciable amount of energy because of its large mass. As a result, the sum of the energy of the degraded electron and the energy of the emitted quantum is, to a good approximation, equal to the energy of the incident electron. Multiple interactions in the synchrotron target can be avoided by use of a sufficiently thin target.

The electrons emerging from the target after interaction are analyzed by the guide field of the synchrotron, electrons of different energies being physically separated. By placing a detector in the path of certain of these electrons it is possible to detect the creation of quanta of an energy corresponding to the energy of the circulating beam minus the energy of the detected electrons. By using this detector to gate apparatus which is examining effects produced by the x-ray beam, results due to essentially monochromatic gamma rays may be obtained.

THE INTERNAL ELECTRON DETECTOR

In order to obtain gamma rays of as high an energy as possible it is desirable to detect electrons of the lowest possible energy. This would necessitate placing an electron detector inside the synchrotron donut. For a variety of technical reasons having to do with convenience in handling and with assurance of continued synchrotron operation, this step was deemed inadvisable, and the electron detector was located outside of the donut. To avoid loss of efficiency due to vertical defocusing of the electrons by the fringe magnetic field, the detector was placed directly against the wall of the donut. Finally, the dual considerations of available space and of having sufficient electron energy to penetrate two centimeters of glass donut wall without excessive scattering dictated placing the detector in such a position that it would receive electrons of about 100 Mev when the synchrotron operated at full 310-Mev excitation. The corresponding monochromatic gamma-ray beam had an energy of roughly 200 Mev.

The electron detector was constructed by using a stilbene scintillation crystal mounted on a $2\frac{1}{4}$-inch diameter Lucite light-pipe and a 5819 photomultiplier. To remove the photomultiplier from the fringe field of the magnet, the Lucite light-pipe was required to be about three feet long and additional magnetic shielding was needed around the tube. Care was taken to provide the 5819 with a low-resistance bleeder to avoid variations of tube voltages at high counting rates. Two stilbene crystals, each 4 cm in diameter, were provided. The length of one of these was 2 cm while the other measured 4 cm. Either crystal could be used. When in position the crystal was oriented with the electrons entering along a diameter so that the longer crystal would intercept a larger band of electron energies.

To test the operation of the scheme and the quality of the resolution, the Cornell pair spectrometer[9] was used in the manner described earlier.[10] The spectrometer was located in the beam and a thin (10-mil) Cu foil was used as a radiator. The synchrotron target consisted of a 12-mil Ni foil. Figure 1 shows the geometry and the circuit arrangement which was employed. Pulses from the central channel of the pair spectrometer were counted in coincidence with pulses from the internal electron detector, hereafter referred to as the pit counter. This coincidence rate was then observed as the magnetic field of the pair spectrometer was varied. The known energy calibration of the pair spectrometer allowed this coincidence counting rate to be converted into a measured gamma-ray spectrum.

To minimize random coincidences the synchrotron beam was spread over about three milliseconds in time by shaping the rf envelope. Even then the resolution of the electronics was sufficiently slow (about one microsecond) to necessitate running the synchrotron at a very low beam of less than 10^6 effective quanta per minute. Maximum counting rates were a few per minute.

Results of these energy resolution measurements are given in Fig. 2. The results shown include the resolution of the pair spectrometer which is approximately triangular with a 10 percent full width at half-maximum. In order to be able to estimate the true gamma-ray spectrum, a theoretical synthesis of the line shape was attempted. The results are shown in Fig. 3. One theoretical curve, $J(E)$, represents the spectrum as it would be seen by the pair spectrometer and is a reasonable fit to the experimental data. The other curve, $S(E)$, is the gamma-ray spectrum with the effects of the resolution of the pair spectrometer not included and has been assumed to represent the true gamma-ray spectrum for later theoretical work. Both the data presented here and the theoretical curves are for the 4

[9] DeWire, Ashkin, and Beach, Phys. Rev. 83, 505 (1951).
[10] J. W. Weil and B. D. McDaniel, Phys. Rev. 86, 582 (1952).

cm crystal which was used in all following work in order to obtain the higher counting rate which results.

FAST COINCIDENCE CONSIDERATIONS

Keck's data for photoproduction of protons indicated that for a reasonable solid angle subtended by the proton detector and for about a 20-Mev detection interval, more than 10^6 effective quanta were required to produce one proton. If roughly one-tenth of these protons is produced by quanta lying in the energy band detected by the monochromatic gamma-ray scheme, then a beam of over 10^7 Q per minute is required for a counting rate of one per minute with one hundred percent efficiency in all detectors.

It can be shown that, independent of the spectral efficiency of the pit detector, the chance-to-true or real-to-random ratio in the counting circuits will be given approximately by

$$\frac{1}{2KT\ln(E_0/E_1)},$$

where T is the resolution of the coincidence circuits; K is the instantaneous beam intensity in effective quanta per second; and E_0 and E_1 are, respectively, the maximum bremsstrahlung beam energy and the effective low-energy cutoff of the external counter. Because of the duty cycle of the Cornell synchrotron of about 1/15 for a three-millisecond beam and because of the 30-cycle repetition rate, the instantaneous intensity must be multiplied by a factor of about four to obtain the number of effective quanta per minute. In an experiment of the type currently performed on synchrotrons the factor due to the spectral sensitivity of the external detector will not give more than a factor of two in real-to-random ratio. Thus, in order to obtain the necessary beams of about 10^8 effective quanta per minute, coincidence resolving times of the order of 4×10^{-9} second are needed.

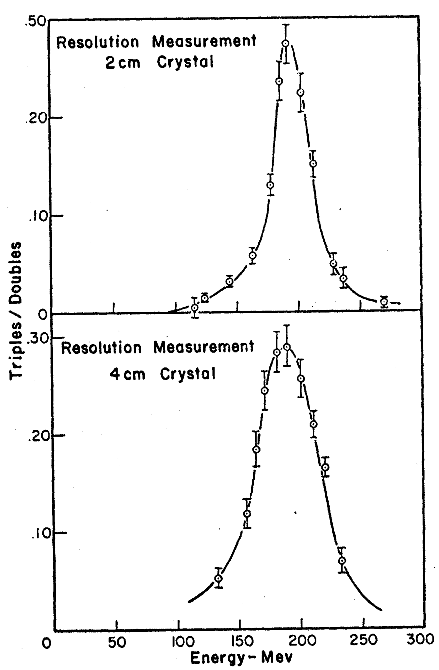

FIG. 2. Line shape of the monochromatic gamma ray as observed with the pair spectrometer. Curves are given for two crystals which intercept different fractions of the internal electron spectrum. The 4 cm crystal was used in the photoproton experiments.

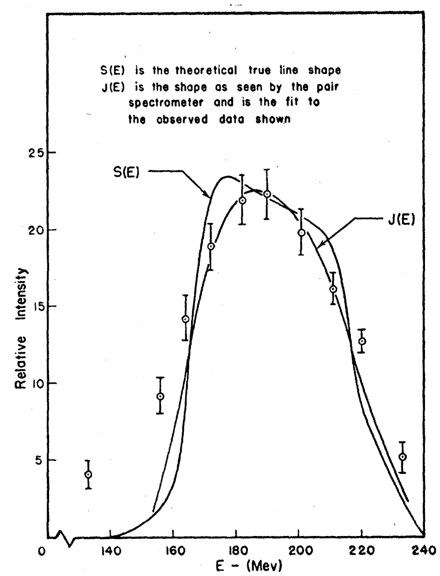

FIG. 3. Theoretical resolution for the monochromatic gamma-ray technique.

The coincidence circuit first constructed was of the Bell and Jordon type in which the incoming negative signal is used to cut off a pentode, the pentode plate signal being clipped by a shorted stub and mixed with a similar signal from the other input. A diode discriminator, followed by suitable amplification and further discrimination, then examines the pulses from the pentode plates. Coincidence pulses, being the sum of identical signals from the two input tubes, are twice the height of the singles pulses and may be distinguished accordingly. This type of circuit proved to work quite nicely at short resolving times, but was found to have two important difficulties. Primarily, the input grids are normally biased at their point of maximum sensitivity with the result that if they are connected to a source of signals which contains a very large amount of small-amplitude, spurious signal (such as the pit counter), the pentode is continually being cut off by this background. The resulting singles rate is much higher than the true singles rate due to the electrons of interest, and the random rate is correspondingly much too high. Secondly, the two-to-one ratio of coincidence-pulse amplitude to singles-pulse amplitude was poor in that the discriminator time constant would stretch the singles pulses, so that at high input rates singles feed-through would appear. It was thus desirable to find a coincidence circuit which could be biased off to avoid seeing the spurious background from the pit counter and which would not feed through.

The requirements for a satisfactory coincidence circuit for this application are quite different from those for situations usually published in the literature. Not only must the circuit be able to distinguish the relative times of arrival of input pulses to a few times 10^{-9} second or better, but it must be able to do so at a very high rate (many times per microsecond). Some of the coincidence circuits available, while able to distinguish relative times of arrival to a fraction of a millimicrosecond, must take about a microsecond to do so and would thus be useless at very high counting rates.

The circuit finally adopted for use was of the 6BN6 type similar to that of Fischer and Marshall[11] (see Fig. 4). Here the input grids may be biased off and are thus insensitive to small-amplitude noise. In addition the ratio of the amplitudes of coincidence pulses to singles pulses is much larger with the result that for properly biased tubes with properly limited input pulses singles feed-through is entirely absent.

For correct operation of such a 6BN6 circuit, the input pulses should be over 6 volts. To get pulses of this magnitude it was found necessary to amplify the input pulses since the newer, high-gain photomultipliers were not yet available and since pulsed operation of the present photomultipliers was not practical for a three millisecond counting span. 200-ohm distributed amplifiers were used which would deliver 8 volts positive to an unterminated output. Above this point the amplifiers are badly nonlinear and thus provide a poor sort of limiting which is effective if the input pulses do not vary too drastically in amplitude. Since the pulses from the pit counter were all roughly the same height, this limiting was satisfactory for use there, where the high rate would have precluded the use of any more normal form of limiting.

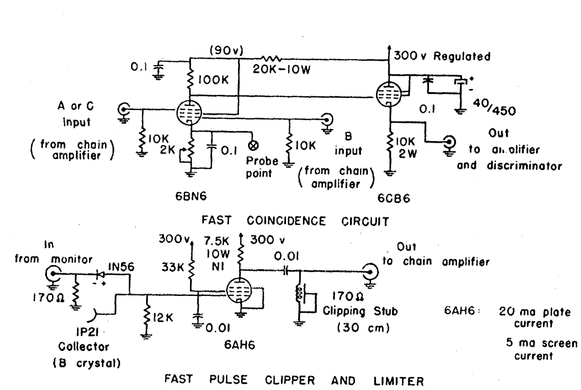

FIG. 4. Electronics associated with the fast coincidence work. Input pulses to the fast coincidence circuit are positive and about 8 volts in amplitude.

[11] J. Fischer and J. Marshall, Rev. Sci. Instr. 23, 417 (1952).

In all the work to be described two complete coincidence circuits were used, with one serving as a delayed or random channel. The coincidence tubes were so arranged that the signal from the external counter could be applied directly to the appropriate grid of both 6BN6's simultaneously. Since this pulse was in general faster than the pulse from the pit counter, the slight additional capacitive loading did not prove to be a limitation on the resolving time. The pulses from the pit counter required amplification through two chain amplifiers in series. The output of the first of these amplifiers was split in a constant-impedance network and each of the two output signals was fed to a separate chain amplifier for the remaining amplification. Each of these amplifiers then drove a single grid in one of the 6BN6 coincidence tubes. It was possible to insert different lengths of delay cable in the two parallel pit inputs in order to set up either channel as a random channel. By varying the delay in the external counter side, both channels could be moved together.

Output pulses from the 6BN6's were stretched to one microsecond in the plate circuit of the 6BN6, amplified by 501 amplifiers, and then discriminated suitably. The use of "slow" amplifiers is found to be important here because the coincidence pulse amplitude is not much larger than the amplitude of the capacitive, singles feed-through pulses, although, because they are conductive in nature, the total area under them is much larger than the area under the feed-through pulses. Hence an amplifier which integrates over a time long compared to the capacitive feed-through-pulse duration is necessary.

The characteristics of the 6BN6 are useful in another fashion. While there is considerable capacitive coupling between the third (quadrature) grid and the plate, the capacitance between the first grid and the plate is negligibly small. Thus the high-counting-rate source (the pit counter) can be connected to the first grid to avoid capacitive pulse pile-up in the integrating amplifiers which follow. The low counting-rate input is connected to the third grid. Very large pulses on the third grid can sometimes feed through capacitively and be recorded. It has been found necessary to provide effective limiting action on this signal input. A 6AH6 clipper-limiter, as shown in Fig. 4, has been used very successfully. No trouble with feed-through was ever experienced with this arrangement.

A resolving time of about 4 to 5×10^{-9} second was used throughout. Because the input pulses were not square but bell-shaped due to the chain amplifiers, the resolving time was to some extent a function of the gain and of the discrimination following the 6BN6. Thus, the use of a random channel was imperative. The length of cable used in forming the delay channel relative to the true channel was 560 cm, corresponding to the time of one revolution around the synchrotron of the electrons in the circulating beam. This length of cable was used to avoid false random rates in the event that the beam from the synchrotron was bunched as it traveled around the machine just before hitting the target. In the stable orbit the beam is sharply bunched, but as it spirals in and is lost from the synchronous rf cycle this bunching would be expected to decrease. A measurement was made of the variation of random rate as a function of delay cable used, using signals from the pit counter and from an external detector situated directly in the beam. A ten percent variation of accidental rate as a function of delay was observed, even when the beam was spread to a full three milliseconds. Thus, to avoid false measurements in the random channel a delay equal to one rf cycle was always used.

As a preliminary exercise in the handling of both the monochromatic gamma-ray technique and the fast coincidence apparatus, a measurement was made of the velocity of 190-Mev light quanta.[12] A value for the velocity was obtained of $(2.974\pm0.03)\times10^{10}$ cm/sec.

In the study of photoprotons the fast coincidence circuit was used to record the simultaneous arrival of electrons in the pit counter and protons in the external detector. The identification of a proton required three counters forming a telescope, so that the fast coincidence indicated only the occurrence of a monochromatic gamma ray and some event in the telescope which could produce a sufficiently large pulse in the individual crystal which provided the fast external output. The fast output could have been taken from either of the two counters in the proton telescope which were counted in slow coincidence with each other. In practice it was found that the use of the rear of the two coincidence crystals cut down the counting rate in the external detector input to the fast circuit and thus decreased the random coincidence rate. Pulses from the second crystal were taken off the collector for the fast coincidence and off the last dynode for the slow coincidence circuitry which was used to detect the protons. Because very large pulses could occur in this crystal, the fast clipper-limiter described earlier was used in this fast coincidence output. At no time did the counting rate in this crystal come near saturating the clipping tube.

It was found during the initial runs on the photoproduction of protons from carbon that it was not possible to reproduce the data to a sufficient accuracy, and analysis of the data indicated a drifting efficiency in the fast coincidence circuitry. With a choice of either attempting to find the instability or monitoring the fast coincidence efficiency in some fashion, the latter was chosen as providing a more certain solution to the problem.

A fast monitor would also have another advantage in the present experiment. This fast monitor could be calibrated in terms of absolute intensity in the monochromatic gamma-ray beam and would allow absolute measurements to be made directly.

[12] D. Luckey and J. W. Weil, Phys. Rev. 85, 1060 (1952).

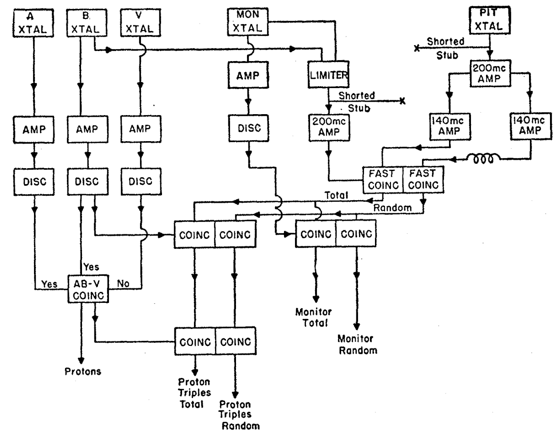

FIG. 5. Complete block diagram of the electronics. Each fast coincidence circuit indicated is actually a coincidence circuit (Fig. 4) followed by an amplifier and a discriminator. All six discriminators have provision for being gated by the floating trigger from the synchrotron, so that they are sensitive only during the period surrounding the beam pulse.

To provide such a monitor a separate, fixed, stilbene crystal is allowed to observe an independent graphite target situated in the beam. The signal from the 1P21 photomultiplier associated with this crystal is mixed, through a short terminated cable and a 1N56 diode, with the signal on the grid of the clipping tube which comes from the second crystal in the proton telescope. This is indicated in Fig. 4. These pulses go through the fast coincidence circuitry in exactly the same manner as the pulses from the proton-detection crystal itself. After detection in the fast coincidence circuit the resulting coincidence pulses (now about one microsecond long) are sent to a sorting circuit consisting of a number of coincidence tubes. If the fast coincidence signal arrives at the same time as a pulse from the slow output of the second proton-detection crystal, it is sorted out as a coincidence having to do with proton detection. If the fast coincidence arrives in time with a pulse from the slow output of the monitor crystal, it is sorted out as a monitor coincidence. The net monitor count should be a steady counting rate independent of anything done to the proton telescope or to the proton target. Variation in the net fast monitor counting rate should then be the result of either variation in the beam intensity or variation in the fast coincidence efficiency. The only changes in the fast coincidence circuitry not followed by the monitor would be those in the second proton-detection crystal itself. Since all phototubes were operated off the same high-voltage supply, these remaining variations should be cancelled out to first order.

Some idea of this monitor technique can be obtained from Fig. 5 which shows a block diagram of the complete circuitry. In addition to the outputs shown the monitor circuit was provided with a slow output for recording monitor singles.

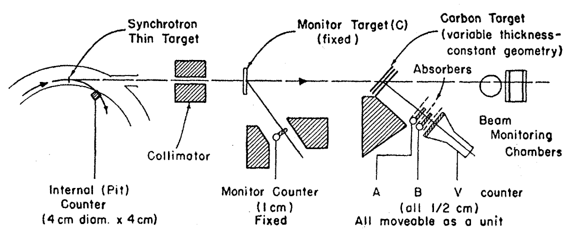

FIG. 6. Schematic of the experimental geometry. All crystals are stilbene.

An absolute calibration of the monochromatic beam intensity was obtained by placing the three-crystal telescope used in the proton work directly in the beam. The front crystal was used as a veto counter while the rear two were counted in coincidence. All three crystals were set to have high efficiency for counting individual electrons of minimum ionization. A curve was then taken of counting rate as a function of Pb converter placed between the front two crystals. The slope of this curve provides an absolute calibration of the beam in terms of the known interaction cross section for gamma rays of this energy in Pb as measured by DeWire, Ashkin, and Beach.[9] All this was done without disturbing the monitor counter so that the monitor counting rate (singles) could be calibrated directly in terms of monochromatic beam intensity. Because the monitor crystal was not located in the beam, a number of intermediate monitors had to be used because of the very low-beam intensity at which this measurement was necessarily made. The very low intensity also avoided any possible corrections due to random coincidences. A straight line was observed as a function of thickness of Pb and the resulting calibration is estimated to be good to about seven percent.

It is possible to use this calibrated monochromatic gamma-ray beam for measurements of the efficiency of various detectors for quanta of this energy. Some work of this nature has been done by A. Silverman and B. D. McDaniel and has been referred to by Cocconi and Silverman.[13]

PHOTOPROTONS FROM CARBON

The telescope used in observation of the photoproduction of protons contained three scintillation counters. The first two were stilbene crystals 0.5 $\times$3.5$\times$5.0 cm mounted on 1P21 photomultipliers. The third counter was a large anticoincidence counter made up of a 5819 receiving light from a mosaic of four crystals similar to those in the first two counters. The effective area of this veto counter was 7$\times$10 cm. This counter was found to have very good sensitivity and resolution over its entire area.

The first two counters, A and B, were counted in coincidence with each other and in anticoincidence with the third, V, counter. The resulting AB-V signal was used in the conventional manner to select protons of a given energy by measuring the specific ionization of particles with a fixed residual range. Copper absorbers were used to vary the telescope settings. In making the various preliminary settings on the telescope care was taken to insure that the effective biases in all counters were set in the slow electronics rather than in the more unstable and less precise fast-coincidence circuitry.

In practice it was found necessary to use a geometry in which the telescope subtended a rather large solid angle at the target. Reduction of this solid angle was not possible because of the low counting rates which resulted. Hence the angular resolution used was rather poor, about $\pm$15 degrees. In order to be able to line up the apparatus easily, slab targets were used where possible. These were set perpendicular to the axis of the telescope. However, because of the rather wide variation of target thicknesses encountered (from 0.75 cm to 2.50 cm) the geometry of the experiment would have had to be calibrated for each target thickness. To avoid this, variable-density, constant-geometry targets were constructed.

For the angular distribution measurements a cylindrical target 2.5 cm in diameter was used, placed with its axis perpendicular to both the beam direction and the telescope axis. This target necessitated careful alignment of the beam in order to prevent changes in the effective spectrum of protons during observation at various angles.

The geometry of the entire arrangement as it was used for the energy spectrum measurements at 60 degrees is shown in Fig. 6. The beam from the synchrotron target is collimated by a one-inch Pb collimator and then strikes the auxiliary graphite target used for the monitor. This target was roughly 0.5 inch thick. The beam then strikes the target used for the production of protons and passes through into several auxiliary monitoring chambers. Both the monitor crystal and the proton telescope were surrounded by Pb shielding to protect them from stray background and to prevent them from seeing the incorrect target.

In addition to the fast coincidence connections mentioned earlier, all crystals except the pit counter had "slow" outputs which were connected through amplifiers to discriminators. The outputs of the A, B, and V discriminators were used to provide an AB-V signal indicating the arrival of a proton. This signal was then mixed with the appropriate fast coincidence signal to give the proton triples signal which indicated the production of a proton by a monochromatic gamma ray. The full block diagram of the electronics is given in Fig. 5.

Because of the complexity of the apparatus and because of the low real-to-random ratio in the fast circuit it was found necessary to keep continuous check on the functioning of the electronics. The two fast coincidence circuits which provided the real and random

[13] G. Cocconi and A. Silverman, Phys. Rev. 88, 1230 (1952).

coincidence counting rates had their functions interchanged at regular intervals by removing the extra delay cable from the random side and placing it into what had been the real side. In addition, all data for the energy distribution of the photoprotons was taken in pairs of points, with the telescope settings for two adjoining energies being identical except for the insertion or removal of additional Cu absorber from in front of the entire telescope. In both of these ways checks on the internal consistancy of the data were available.

A typical single run on any point would take about one hour with from 40 to 120 real triples being recorded and with roughly one-quarter to one-third as many being recorded in the random channel.

Throughout the experiment calibration runs with delay cables in both fast coincidence circuits were taken to determine the relative widths of the two channels. This information was then used to correct the data taken in regular runs for any disparity in channel widths.

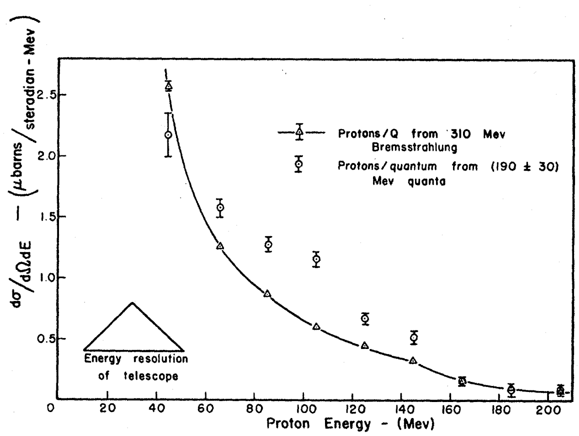

FIG. 7. Proton energy distributions from carbon at 60±15 degrees.

All data were corrected for random counts and for nuclear absorption in the telescope. Absolute calibration of the monochromatic beam intensity was made in the manner described above. The absolute calibration of the intensity of the full bremsstrahlung beam was made using the standard Cornell ionization chambers.

RESULTS AND INTERPRETATION

The results obtained from the energy spectrum measurements are given in Figs. 7 and 8. On each graph the results from both the full bremsstrahlung beam and the monochromatic gamma ray are given for purposes of comparison. The indicated errors are standard deviations due to counting statistics and indicate the relative error in the position of the points. In addition, from the absolute calibration, there is an uncertainty of seven percent in the numbers used and a rough uncertainty of perhaps 20 percent because of possible errors in the estimate of solid angle of the target subtended at the telescope. The net absolute error of the cross sections is estimated to be about 25 percent.

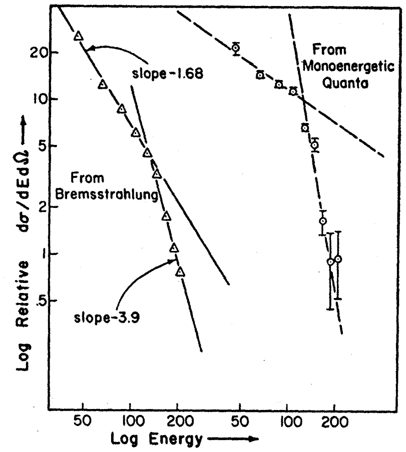

FIG. 8. Proton energy distributions from carbon at 60±15 degrees. This is a log-log plot of the data given in Fig. 7.

From the linear plot of the data it can be seen that the two energy distributions obtained at 60 degrees for the two kinds of incident gamma-ray spectra are not the same, there being more protons at intermediate energies in the case of the monochromatic incident spectrum. The log-log plot shows the more conventional features of such spectra. In agreement with previous workers the proton distribution from incident 310-Mev bremsstrahlung is seen to fall essentially on two straight lines. The slope of the low-energy line is found to be -1.68 in good agreement with the -1.7 found at 67 degrees by Keck,[2] by Rosengren and Dudley at 45 and 90 degrees,[3] and by Levinthal and Silverman at 90 degrees.[1] The upper part of the curve has a slope of -3.9 which agrees well with the results of Rosengren and Dudley and is not in serious disagreement with the data given by Keck. Levinthal and Silverman did not extend their measurements to these higher proton energies. In agreement with all these workers, the break in the spectrum appears to come at roughly half the maximum energy of the bremsstrahlung distribution. Recently Wattenberg, Feld, and Godbole[4] have reported results at 30 degrees in qualitative agreement with those given here but differing somewhat in the actual numerical values obtained.

The proton spectrum resulting from bombardment with monochromatic gamma rays also falls roughly on two straight lines with, however, different slopes from the bremsstrahlung case. The low-energy portion of the curve is flatter, and the high-energy portion falls off more rapidly. The break occurs somewhere in the vicinity of 100 or 110 Mev.

No attempt will be made to explain the bremsstrahlung-produced spectrum because of the interpretive difficulty mentioned earlier. Rather, an effort towards explaining the results from the monochromatic beam will be made in detail with the hope that any success

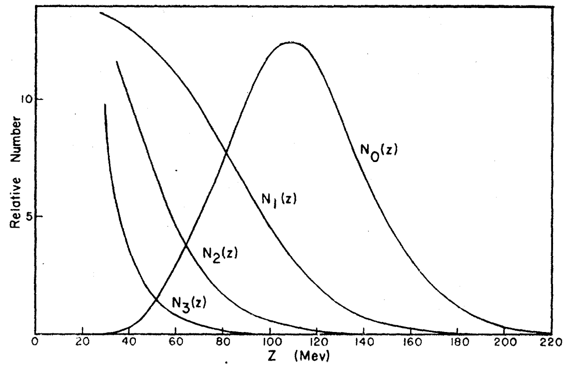

FIG. 9. Theoretical energy distributions of protons from disintegration of a pseudo-deuteron within the carbon nucleus, for various numbers of collisions during escape from the nucleus.

along this line may be extended to the bremsstrahlung results.

As has been noted by others, perhaps the most suggestive thing about the results of energy distribution measurements of protons from carbon has been the location of the break in the log-log plot. This feature would seem to indicate that the recoil from proton emission was being taken up by some light sub-unit of the nucleus. Specifically, if the deuteron photodisintegration were being studied at 60 degrees, a peaked spectrum centering at a little over 110 Mev would be expected for incident 200-Mev quanta. The fact that the break in the observed energy distribution comes just at this point has led to an attempt to construct the experimental results in terms of a two-particle model.

Three effects will modify the spectrum of protons observed in the laboratory from such a deuteron interaction in carbon. The motion of the individual nucleon at the time it is struck will smear out the line spectrum of protons otherwise expected from a deuteron disintegration. In addition, the motion of the center-of-mass of the pseudo-deuteron will smear out the proton energy spectrum observed at a fixed laboratory angle. It can be shown that the second of these two effects is much more important because of the heavier mass of the moving system, with the result that the motion of the individual nucleon will not appreciably affect our results and will be neglected in the following calculations. The third effect due to the motion of the nuclear particles is that this motion will shift the center-of-mass energy available to the reaction and will therefore affect the cross section somewhat. It will be assumed that the energy dependence of the cross section is sufficiently flat to be neglected. If the deuteron model is to be taken literally, some speculative support for this assumption can be obtained from the flat energy dependence of the deuteron photodisintegration cross section as measured at these energies.

The momentum distribution of the center-of-mass of the pseudo-deuteron can be obtained by a folding of the momentum distributions of the two participating nucleons. An individual nucleon is assumed to have a momentum distribution given by a Fermi distribution at zero temperature. While this is not strictly correct it should be pointed out that the 8-Mev temperature often used in the literature is not correct either in light of the model which is being considered. More important, however, is the fact that the calculations to follow are extremely insensitive to the detailed shape of the momentum distribution assumed, so long as the general shape and approximate relation of the various portions of the distribution are maintained. The resulting momentum distribution for the center-of-mass of the pseudo-deuteron is denoted by $P(p_d)$.

The spectrum of protons ejected from the pseudo-deuteron is then given by the expression

$$X(E_p)=\int_{E'} P(p_d)\frac{dp_d}{dE_p}S(E')dE',$$

where $X(E_p)$ is the spectrum of protons emerging at the angle of observation, E' is the incident gamma-ray energy, $S(E')$ is the spectrum of incident gamma-rays, and E_p is the observed proton energy. The gamma-ray spectrum which has been used in the present calculations is derived from the theoretical fit to the monochromatic gamma-ray spectrum measurements.

If this integral is carried out numerically a spectrum of protons from the pseudo-deuteron is obtained. A certain fraction of these protons will escape from the nucleus without making further collisions. The spectrum of these protons is called $N_0(E)$ and is shown in Fig. 9. The energy scale has its zero referred to the bottom of the well within the nucleus and is not yet the energy in the laboratory. This energy may be converted to the laboratory system by subtracting some average nucleon binding energy. This subtraction is to allow for the depth of the well minus some average energy of the individual nucleons within it and is a quantity not already taken into account in the above calculations involving the motion of the center of mass of the pseudo-deuteron. The amount to be subtracted is roughly 15 Mev.

In a manner adapted from Keck[14] it is possible to compute the energy spectrum of protons which are scattered on the way out of the nucleus. This is done by computing the escape probability of nucleons from a spherical nucleus using a collision cross section derived from the work of Goldhaber[15] and of Fernbach *et al.*[16] It is then assumed that protons of energy E which do make a collision are scattered with equal probability into any portion of the energy interval from 20 Mev to $E-10$ Mev. The exclusion of regions at both ends of the energy scale is the result of the use of a Fermi gas model. A correction factor is then added to the scattering

[14] J. C. Keck, Cornell University thesis, 1951 (unpublished).
[15] M. L. Goldhaber, Phys. Rev. **74**, 1269 (1948).
[16] Fernbach, Serber, and Taylor, Phys. Rev. **75**, 1352 (1949).

calculation to allow for the fact that a proton may collide with another proton thus giving rise to two protons emitted. This factor also includes the initial production of an equal number of neutrons which can then produce protons upon scattering. This factor is taken to be 2 for one collision, 4 for two collisions, and 8 for three collisions. Because all of the above scattering calculations are admittedly rough and because of the simplification involved, it is also assumed that there is no angular effect in the scattering, that is, that in-scattering into the solid angle of observation equals out-scattering.

With these approximations the relative magnitudes and shapes of the spectra of protons after one, two, and three scatterings can be computed and are shown in Fig. 9 as N_1, N_2, and N_3, respectively. The sum of all four of these spectra then roughly represents the spectrum of outgoing protons. By subtraction of 15 Mev from the energy of each proton the spectrum is then converted into an energy spectrum in the laboratory.

Finally, these resulting spectra are to be folded with a representative resolution function for the proton telescope. The energy resolution function of the telescope is roughly triangular with full width at half-maximum of 20 Mev. Because of the correlation between proton energy and angle in the pseudo-deuteron disintegration assumed, an additional energy spread is caused by the poor angular resolution of the telescope. To allow for this the net resolution has been taken to be triangular with a 30-Mev full width at half-maximum. The results of this folding are given in Fig. 10 where both the entire spectrum and the spectrum of those escaping without scattering are shown. While this last folding has smoothed the curves out a little, it is seen that the results are largely insensitive to any detailed choice of telescope resolution function. The curves have been normalized for best fit to the monochromatic gamma-ray data which are also shown on the same graph. The theoretical curve has also been arbitrarily moved up the energy scale by 5 Mev to improve the fit. This amount is within the uncertainties involved in absolute calibration of the gamma-ray energy since the synchrotron target was moved and certain organic modifications of the synchrotron were made in the period between the pair-spectrometer measurements of the monochromatic spectrum and the measurements of the proton energy spectrum.

The success of the fit to experiment is indeed surprising, but a rather careful distinction must be made in the interpretation of the significance of this fit. The upper portion of the curve shows a nice fit which is probably rather strongly indicative of the approximate correctness of the deuteron model. It is probably true that any momentum distribution reasonably similar to the Fermi distribution would give as good a fit to the present data. But the general confirmation of the type of model is probably significant. On the other hand, the good fit to the lower portion of the curve, where the large scattering contributions have been added, must be considered largely fortuitous. The magnitude of the scattering corrections is extremely sensitive to the exact choice of escape probabilities, and probably the only important result is that such calculations can indeed give curves of the general character of those which are observed. These curves should not be taken to exclude the possibility of a significant contribution from other processes in the low-energy region.

The area under the curve of those protons which have escaped without scattering is some 76 microbarns, representing 55 percent of the protons initially produced from the assumed pseudo-deuteron process. This means that the integrated cross section for the photoproduction of protons at 60 degrees from the carbon nucleus by the mechanism under discussion is about 138 microbarns. If this cross section is then divided by the number of effective deuterons in the carbon nucleus (shown by Levinger[7] to be 1.6A if the deuteron is composed of a proton and a neutron) a cross section for the photodisintegration of the pseudo-deuteron within the carbon nucleus can be obtained. The value obtained here is 7 microbarns/Mev-steradian with an estimated absolute error somewhat larger than 25 percent. It is interesting to note that this cross section is essentially within the experimental error of measurements made by a number of workers of the cross section for the photodisintegration of a real deuteron at this energy and angle.[17–21] Of course, if the pseudo-deuteron is also allowed to be a pair of protons or a pair of neutrons the cross section resulting from our measure-

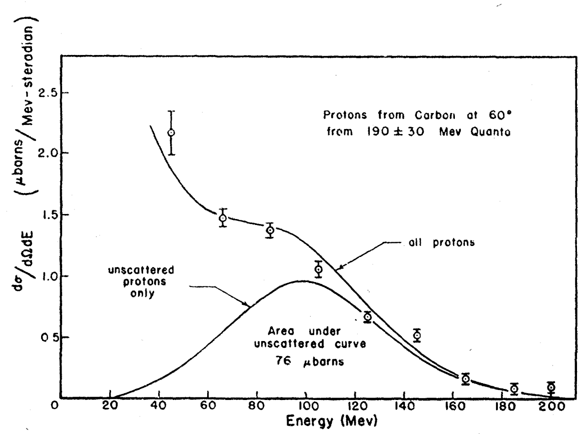

FIG. 10. Theoretical synthesis of the energy distribution. The curve for all protons is the result of the full theoretical synthesis and represents the attempted fit to the data. The curve for unscattered protons is given for comparison and for use in computing an effective cross section for photodisintegration of the pseudo-deuteron within the carbon nucleus.

[17] J. C. Keck and R. M. Littauer, Phys. Rev. **86**, 1051 (1952).
[18] S. Kikuchi, Phys. Rev. **85**, 1062 (1952).
[19] W. S. Gilbert and J. W. Rosengren, Phys. Rev. **88**, 901 (1952).
[20] T. S. Benedict and W. M. Woodward, Phys. Rev. **85**, 924 (1952).
[21] O'Neill, Perry, and Woodward (private communication).

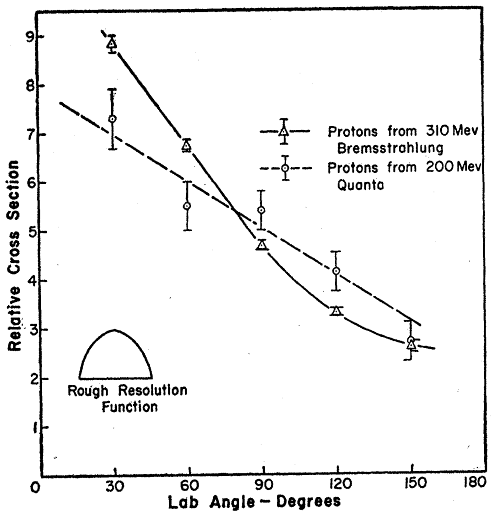

FIG. 11. The angular distribution of photoprotons of 70±17 Mev from carbon. The dotted line is a straight line drawn for purposes of comparison only through the data from an incident monochromatic gamma-ray spectrum.

ments would be somewhat lower, but the data here and the present data for the photodisintegration of the deuteron do not allow a real distinction to be made.

Keck and Perry[5] at this laboratory have also measured the energy distribution of protons produced at 60 degrees by monochromatic gamma rays. They used the bremsstrahlung subtraction technique and obtained results from quanta centered about 280 Mev. Their results, combined with theoretical considerations similar to those used here, agree in principle with those given above.

Figure 11 shows the angular distribution observed for 70-Mev protons. It is possible to say, first, that the present distribution is not inconsistent with a two-particle model which breaks up isotropically in the center-of-mass system. The various resolution functions and the nuclear scattering would perhaps be expected to make the distribution somewhat more isotropic than the observed curve, but this is not entirely clear. In addition it is not unlikely that the experimental point taken at 30 degrees is too high by 10 percent or so because of the large electron background experienced in this position with the rather poor angular resolution of the apparatus and the consequent rather poor resolution of protons in the pulse-height spectrum. Because of this perhaps all that can be said is that the angular distribution of protons from the monochromatic gamma-ray spectrum is not in disagreement with the model proposed for explaining the energy distribution.

The angular distribution data taken for protons produced by the entire bremsstrahlung spectrum are in essential agreement with those given by other workers. As expected, it shows a sharper peak in the forward direction and a lower cross section in the backward direction when compared to the results from monochromatic quanta.

EVALUATION OF THE MONOCHROMATIC METHOD

It has been established that by this technique one may perform experiments with a narrow spectrum of quanta selected from the bremsstrahlung spectrum. But there are a number of additional facts which should be noted in comparing this technique with some other approach, such as the difference spectrum technique. First, the apparatus is complex, not only in magnitude but also in the interlacing of the various functions. This is clear from examination of the block diagram of the electronics discussed elsewhere. Excluding the pulse-height analyzer, the electronic equipment devoted solely to this experiment contained some three hundred vacuum tubes. Secondly, with the duty cycles available from present synchrotrons and with the present limitations on coincidence resolving times, the monochromatic beam intensity (and hence the net counting rate) is severely limited. About four weeks of continuous running time were devoted to setting up for and taking the energy distribution curve, even after all difficulties had been eliminated and the experiment had been shown to be working. It is probably so that the same results on photoproduction of protons could have been obtained more conveniently and more rapidly by the difference spectrum technique. However, it was felt a valuable check to be able to obtain results by a new method in order to prove the validity of the difference technique.

For experiments requiring only very low-beam intensities (such as the calibration of the efficiency of gamma-ray counters) the electronics may be greatly simplified to permit rapid and easy measurement. Even for those experiments requiring greater beam intensities, the occasion may arise for the application of the technique. The present technique should also be re-evaluated when some of the higher energy machines come into operation, particularly those of race-track design. In this case much greater convenience in detecting the internal electron would be possible, and running a number of energy channels simultaneously would be a feasible method of significantly increasing the effective counting rates. One may, of course, hope for some improvement in resolving times and coincidence techniques.

We are greatly indebted to Professor P. Morrison for discussions concerning the interpretation of this experiment and to Doctors R. M. Littauer, J. C. Keck, and A. M. Perry for the communication of unpublished experimental results and theoretical calculations as well as their assistance in the design of the circuits. In addition, grateful acknowledgement is made to Professor J. W. DeWire for the use of the pair spectrometer and to the many students and members of the staff who helped operate and maintain the synchrotron.