High Energy Photons from Proton-Nucleon Collisions

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High energy photons (up to 200 Mev) are emitted by various cyclotron targets when these are bombarded by protons with energies greater than 180 Mev. Spectral distributions, angular distributions, and yields are given for various proton energies and targets. Various possible origins are discussed in the light of the experimental observations.

I. INTRODUCTION

In view of the success of the 184-inch synchro-cyclotron in producing the π-mesons observed in high altitude cosmic-ray observations, it seemed worth while to search also for possible evidence bearing on the origin of the soft component of cosmic rays in the collisions of the 340-Mev protons with matter.

The mixed showers investigated by Chao[1] and by Fretter[2] indicate the generation of electronic radiation associated with the events which produce meson showers. One may speculate that this can arise through charge acceleration[3,4] (bremsstrahlung) of the primary proton and of the charged particles ejected in the event,[5] or through the production and self-decay of neutral mesons,[6] or by the excitation of very high energy nuclear states, or by some unidentified process whereby electrons or photons are directly projected from the collision event.

Evidence is here presented for the production of high energy photons in the collision of protons of energies over 175 Mev with the cyclotron target. The yield and the spectrum seem to exclude a bremsstrahlung origin, and a Doppler shift effect excludes a nuclear origin. The observations are consistent with a source associated with proton-nucleon impacts (as distinguished from proton-nucleus collisions).

Although the data at this stage are meager and without high precision, it is considered that they demonstrate an effect worth reporting in preliminary form. Because of extensive development of instrumentation required for further work, a considerable time will be required before a more thorough study can be presented. In the present report experimental details will be minimized, since these must be comprehensively treated in such a subsequent paper.

II. EXPERIMENTAL ARRANGEMENTS

A. Instrumentation

Through the ten-foot concrete shielding of the cyclotron two holes have been provided whose primary purpose is to permit collimated beams of neutrons to emerge from two different target radii. These have been here employed as ports for viewing the target with a pair counter.[7] In Fig. 1 the plan view of the arrangement is evident, and in Fig. 2 a plan view of the pair counter is shown.

For materializing the photons thin sheets of Ta were employed, and for counting the pair electrons proportional counters were used in quadruple coincidence. The fact that the cyclotron beam is pulsed dictates the use of proportional counters rather than Geiger counters with their long dead-time, since the pulse duration of the beam at the target is in the neighborhood of 100 μsec.

As the magnetic flux density is varied, to allow detection of pair electrons of different total energies, the detection efficiency will not remain constant, due to scattering of electrons in the material of the Ta radiator. It would be necessary to correct for this variation in scattering loss by calculations based upon multiple-scattering analysis if a single radiator were employed at various energies. Instead of this, however, in the data presented in Fig. 3 the radiator thickness was adjusted for each mean energy in such a manner as to keep the mean squared angle of scattering constant. This angle is given by

$$\langle\theta^2\rangle_{Av} = a(t/E^2)\ \ln bt,$$

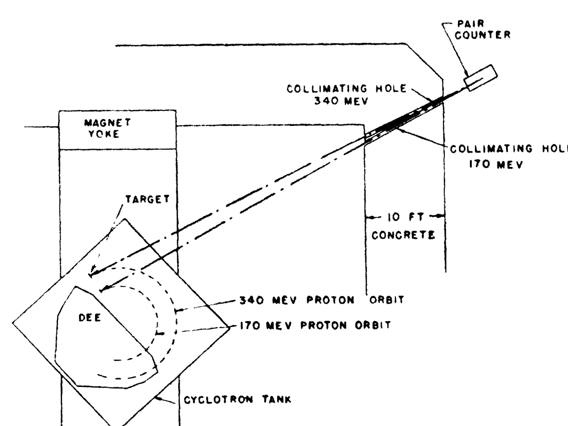

FIG. 1. Plan view of experimental arrangement.

[1] C. Y. Chao, Phys. Rev. **75**, 581 (1949).
[2] W. B. Fretter, Phys. Rev. **76**, 511 (1949).
[3] S. Hayakawa, Phys. Rev. **75**, 1759 (1949).
[4] J. Ashkin and R. E. Marshak, Phys. Rev. **76**, 58 (1949).
[5] L. I. Schiff, Phys. Rev. **76**, 89 (1949).
[6] Lewis, Oppenheimer, and Wouthuysen, Phys. Rev. **73**, 127 (1948).
[7] MacDaniel, von Dardel, and Walker, Phys. Rev. **72**, 985 (1947).

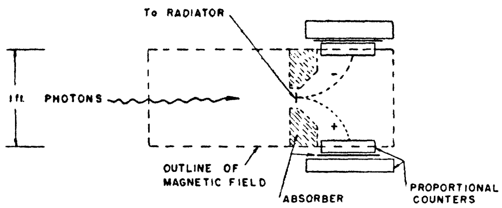

FIG. 2. Plan view of pair counters.

where a and b are constants; and the values of E at which data were taken were so related to the t values of 0.001 in., 0.002 in., 0.004 in., and 0.006 in. as to provide constant $\langle\theta^2\rangle_{Av}$.

The magnetic field dimensions were 12 in.$\times$30 in. $\times 1\frac{3}{4}$ in. When used as shown in Fig. 2, the first half of the field is effective in clearing out electron pairs from the preceding air column and collimating fixtures. This was a necessary precaution with radiators of the thickness and size employed, the radiating area of the tantalum being restricted by their size and by beam collimation to a $\frac{1}{2}$ in.$\times$1 in. rectangle.

B. Corrections to Data

The following factors must be accounted for in obtaining from the monitored quadruple counting rates the data which are presented in Figs. 4 and 5 and in Table I.

1. Scattering losses, unless these are made constant as described above, must be relatively calculated. For the absolute yield data given later the scattering loss must be numerically evaluated.

2. The energy breadth detected varies with the mean energy. Since at relativistic electron energies, $E=300B\rho$ and since the geometry is the same for all energies, $\Delta E/E$ is a constant. For the arrangement of Fig. 2, ΔE is approximately $\frac{1}{3}E$.

3. The photon energy is not uniquely divided between the two electrons of the pair, but will range in its partition all the way from 0 percent and 100 percent for the electron and positron, respectively, to the other extreme; and it is possible to accept in the counters only the fraction allowed by the range of radii which the counter dimensions define.

4. The efficiency of pair production in the radiator will vary with the energy of the photons. Pair production cross sections calculated by Heitler[8] have been used for evaluating the effect of this.

In summarizing these items involved in treating the data, the formula relating counting rate to photon flux incident upon the radiator per unit range of energy at energy E may be expressed as:

$$F(E)=R/(N\sigma_{pp}t)\cdot\Delta E\cdot f\cdot\eta(E,t), \qquad (1)$$

where R=quadruple coincidence counts per second, $\eta(E,t)$=fraction of pairs not lost by scattering, ΔE =energy breadth detected, f=fraction of pairs which are detected, and $N\sigma_{pp}t$=pair production efficiency of radiator.

C. Energy and Angle-of-View Arrangements

The two neutron holes shown in Fig. 1 allow a limited range of proton energies and angles of view to be achieved. The hole directed along the tangent line of the 340-Mev orbit allows, by reversal of the proton beam, angles of view of 0° and 180° with respect to the beam direction. The hole directed along the tangent to the 170-Mev orbit allows targets to be placed at energies between 170 and 340 Mev.

An array of targets which could be raised into position by flip coils was placed along this line of view, with careful attention given to their equivalence from the standpoint of thickness, orientation, and visibility by the pair counter. The energies and associated angles of view for this array were:

175 Mev	2° and 178°
230 Mev	20° and 160°
290 Mev	41° and 139°
340 Mev	47° and 133°.

D. Cyclotron Targets

The high energy photons were observed from any target material, and the relative yields are discussed later. For the array of targets at various energies, each was of carbon, $\frac{1}{2}$ in. thick. The target for which the absolute yield data were most carefully measured was of beryllium, 2 inches in thickness. The energy loss of the 340-Mev protons in 2 inches of beryllium is about 25 Mev.

III. RESULTS

A. Proof of Photon Identity

In order to establish the fact that the quadruple coincidences observed were indeed due to photon-produced pairs, the following kinds of separate observa-

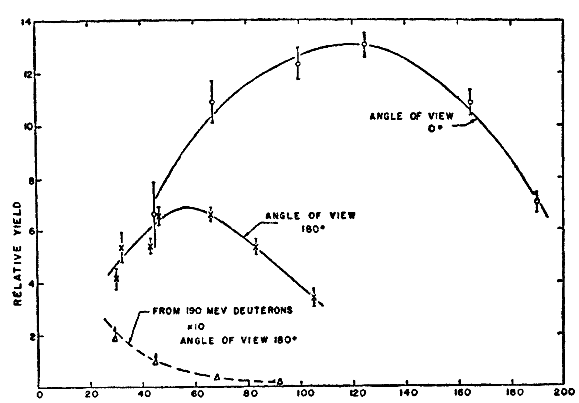

FIG. 3. Relative gamma-yield *vs.* energy from 2-in. Be target, bombarded with 350-Mev protons.

[8] W. Heitler, *Quantum Theory of Radiation* (Oxford University Press, New York, 1936). Second edition.

tions were made and repeated whenever deemed necessary.

1. Tantalum radiator removed. This always reduced the quadruple counting rate to a small number appropriate to pairs from the air plus accidental coincidences.

2. Magnetic field reduced to zero. This left only counts due to accidental coincidences, amounting to 0.1 percent to 1 percent of the normal quadruple counting rate, depending upon the mean energy for which the field is adjusted.

3. Absorber placed in path of one of the pair electrons, with same results as in 2.

4. Attenuation of the photons by Pb and Al studied in good geometry. The measured cross sections for attenuating the pair-producing radiation agree with Lawson's[9] values and are not consistent with any other known radiation.

B. The Photon Spectra and Relative Yields at 0° and 180°

In Figs. 3 and 4 the energy distribution is shown, as calculated relatively from the counting rates by use of Eq. (1), with $\eta(E, t)$ constant as described earlier. The Doppler shift effect upon the relative yields and the positions of the maximum intensity, due to reversal of the beam, is evident and will be discussed in later sections. The data in Fig. 3 also include the spectrum of photons yielded by bombardment of a $\frac{1}{2}$-in. Be target with 190-Mev deuterons. Both the yield, when calculated on an absolute basis, and the spectrum, in the case of deuterons, are consistent with bremsstrahlung.

It will be shown in Section IV that the energy distributions and yields for 0° and 180° become apparently identical when transformed into a coordinate system moving with a relative velocity of $\beta = v/c = 0.32$ with respect to the laboratory in the direction of the incident proton beam.

The relative yields in the 0° and 180° direction were approximately measured by successive runs of the same duration on identical carbon targets, which were then monitored for the annihilation gammas of the 20-minute C^{11} activity produced by the proton beam. The relative activities were considered to indicate relative beam strengths, making possible a comparison of the photon yields. By working in the 340-Mev position at 133°, a comparison with this direction was also included. In Table I, the results are related to those predicted by considering the photons to be emitted with spherical symmetry in a system moving in the proton beam direction with $\beta = v/c = 0.32$, and applying the Doppler corrections to solid angle and energy interval.

C. Photon Yield *versus* Energy

For evident reasons it is not possible with present facilities to employ various proton energies without also changing the angle of view. The angles of view associated with the energies are given in Section II-C, and indicated in Fig. 4.

In order to compute yield *versus* energy data from the curves of Fig. 4, it would be necessary to know the angular distribution of the photons in the laboratory

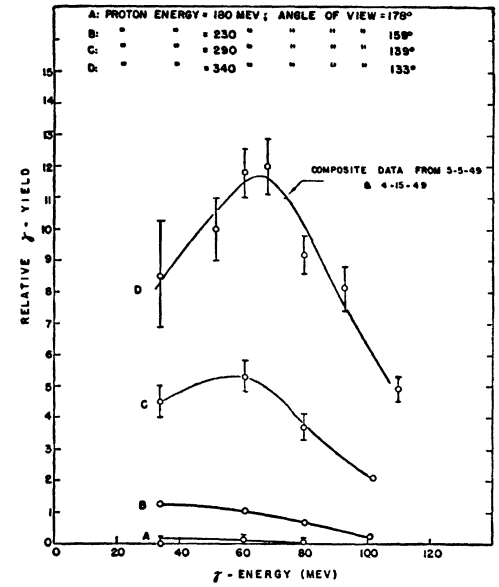

FIG. 4a. Relative gamma-yield from $\frac{1}{2}$-in. carbon target at various proton energies.

system for each proton energy. The meager data presented, however, indicate a yield rising steeply with energy. At 175 Mev the magnitude and spectrum of the photon emission are roughly consistent with proton bremsstrahlung; whereas at the next energy, 230 Mev, the yield has greatly exceeded bremsstrahlung predictions and the spectrum begins to show the characteristic maximum region, departing distinctly from the $1/E$ distribution.

It appears reasonable to state that the onset of the emission of the radiation in question occurs somewhere between 175- and 200-Mev proton energy. Because of the momentum distribution of the nucleons in the target nuclei, a sharp threshold is not to be expected until an experiment with a hydrogen target is performed.

D. Yield *versus* Target Element

In Table II are presented data comparing the relative yields of photons with the relative cross sections for inelastic collision with high energy neutrons for a few elements distributed widely in atomic number.

It will be noted that the bremsstrahlung from deuterons at 190 Mev (proton energy of 95 Mev) gives relative yields similar to the relative inelastic cross sections, whereas the photon emission in the case of the 340-Mev protons increases with Z much more slowly than the cross section for inelastic collision. This suggests that the processes giving rise to the photons are different in the two cases.

[9] J. Lawson, Phys. Rev. 75, 443 (1949).

E. Absolute Yield Data

The curves of Fig. 3 can be given absolute ordinates by evaluation of $\eta(E, t)$. From the proton beam current, target data (2-in. Be), and solid angle data, a cross section for the Be nucleus for production of the photons is computed.

The evaluation of $\eta(E, t)$ was performed by applying multiple scattering analysis to the contribution of electron pairs from an element of the radiator of thickness dx at depth x, finding the mean squared scattering angle with which they emerge, and their probability of both recording in the counters. The fraction of pairs surviving scattering loss is then found by integration (graphical) over the radiator thickness, t. In the case of 0° angle of view, the value of $\eta(E, t)$ was 0.97. It was made approximately constant at all energies by the method mentioned in II-A. In the case of 180° angle of view, $\eta(E, t)$ was 0.84.

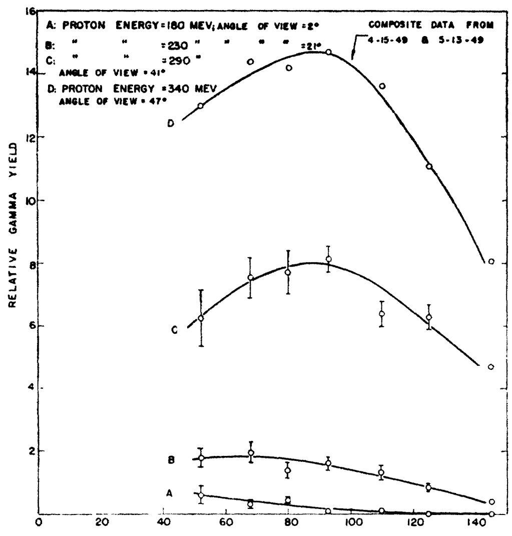

FIG. 4b. Relative gamma-yield from ½-in. carbon target at various proton energies.

The proton current was determined by measuring the C^{11} activity produced in the cyclotron target and using the $C^{12}(p, pn)C^{11}$ cross section at 345 Mev as determined by Peterson.[10]

The resulting cross sections are tabulated in Table III. The coordinate system with $\beta=0.32$ is the system for which the 0° and 180° distributions transform into a unique energy distribution. There is also some evidence for spherical symmetry of photon emission in this system, and this has been assumed in giving the value for total production cross section.

The values in Table III are not good in an absolute sense to the accuracy indicated, but the relative accuracy warrants the figures given. In an absolute sense, these are not to be trusted more closely than a factor of two or three.

IV. ANALYSIS OF RESULTS

If there is some unique coordinate system with velocity βc, in which the photons (or some intermediate particle) are emitted with a spherically symmetric angular distribution, and if $I_c(E)$ is the spectrum of the photons in that system, then the spectrum in the laboratory system at an angle θ will be

$$I(E, \theta)=\frac{(1-\beta^2)^{\frac{1}{2}}}{1-\beta\cos\theta}I_c\left(\frac{1-\beta\cos\theta}{(1-\beta^2)^{\frac{1}{2}}}E\right),$$

where the Doppler shift and aberration effects have been taken into account. The spectra shown in Figs. 3 and 4, in the case of 340-Mev protons, all satisfy the above condition, within the experimental accuracy, if we choose $\beta=0.32$. Figure 5 shows the four 340-Mev spectra of Figs. 3 and 4 transformed to this moving coordinate system. (For the sake of clarity, all curves are normalized so as to have the same value at the peak. Table I gives the measured relative values at the peak.) The reasonableness of this value of β may be seen from the following considerations: The velocity of a 340-Mev proton is 0.67c, and hence, the β of the center of mass of such a proton and a stationary nucleon is 0.39. The nucleons in the target nucleus are not stationary, however, since they have kinetic energies up to about 25 Mev, and hence velocities up to about 0.22c. Now, as shown in Fig. 4, the process leading to the production of these photons is very energy sensitive, and hence, the production of photons presumably occurs predominately in those collisions where the largest amount of energy is available. These collisions are those which take place between a 340-Mev proton and a nuclear nucleon moving in the opposite direction, and hence those which lead to lower values for the velocity of the center of momentum. Since, as mentioned above, nuclear nucleons may have β's of the order of 0.2, a mean effective center of momentum velocity in the range 0.30c–0.35c is quite reasonable.

Figure 4 shows that the yield of photons increases by a factor of about 100 as the proton energy increases from 175 Mev to 350 Mev. The yield for 175-Mev protons is about the same as the yield for 190-Mev deuterons and is consistent with proton bremsstrahlung. If the large increase which occurs beyond this energy is due to some other process, then the threshold for this other process, as has already been mentioned, is somewhere in the neighborhood of 175–200 Mev. If we take 25 Mev as the maximum energy of nucleons in the target nucleus, then the maximum energy available for inelastic processes produced by 175-Mev incident protons is about 170 Mev. This energy is about twice the mean energy of the photons observed and suggests, perhaps, that the photons are produced in pairs, or that an intermediate particle with a rest mass equivalent to

[10] V. Peterson (to be published).

twice the photon energy is involved. It may also be noted that the threshold for producing π-mesons is also about 175 Mev, and that the yield *vs.* energy results are similar.

V. INTERPRETATION OF RESULTS

In this section we shall discuss various possible interpretations of the origin of these photons, and examine how they fit the experimental data at hand.

A. Nuclear Excitation

This possibility may be eliminated almost immediately on theoretical grounds. It may also be eliminated on the basis of some of our results. A very strong evidence against nuclear excitation is the pronounced Doppler shift observed. The shift could not conceivably be appropriate to velocities possessed by a nucleus. Further, if this process were due to some nuclear excitation, then the yield from 390-Mev alpha-particle bombardment would be expected to be greater than the yield from 340-Mev proton bombardment, since the alpha-particle will in general lead to a more highly excited nucleus than the proton. The opposite has been found to be true; 340-Mev protons give a photon yield some 10^3 times greater than 390-Mev alphas.

B. Bremsstrahlung

Calculations by Hayakawa,[3] Marshak and Ashkin,[4] and Serber[11] lead to the result that about one photon in the region of interest of these experiments will be produced in about 10^4 proton-nucleon interactions. In the case of beryllium, which has an inelastic cross section of about 10^{-25} cm^2 (1.0×10^{-25} for 280-Mev neutrons),[12] these results lead to a cross section for high energy photon production of 10^{-29} cm. This is in agreement with our observed cross sections for 175-Mev protons and 190-Mev deuterons. The observed cross section at 350 Mev, however, is about 100 times larger than this predicted value. Further, the shape of the spectra and, in particular, the rapid increase in yield with proton energy do not conform to any known type of bremsstrahlung.

TABLE I. Photon yields as a function of angle.

Lab. angle of view	Relative photon yield	Predicted relative yield
0°	2.1 ± 0.3	2.0
133°	1.1 ± 0.2	1.2
180°	1.00	1.00

TABLE II. Comparisons of yields and cross sections for different elements.

	Be	Cu	Ta
Relative yield per nucleus of 70-Mev photons from 340-Mev incident protons (180° angle of view)	1	2.8	4
Relative inelastic collision cross sections for 280-Mev neutrons	1	5	11
Relative yield per nucleus of photons from 190-Mev deuteron bombardment	1	—	9 ± 1
Relative inelastic collision cross sections for 90-Mev neutrons	1	4.3	8.7

[11] R. Serber (private communication).
[12] J. DeJuren (to be published).

TABLE III. Cross sections per C nucleus for production of photons.

	Lab. system	$\beta=0.32$ system
Differential cross section in cm^2 per Mev per steradian for yield in 0° direction (at the peak)	1.2×10^{-30}	0.85×10^{-30}
Same for yield in 180° direction	0.6×10^{-30}	0.85×10^{-30}
Integrated over spectrum observed at 0° in cm^2 per steradian	1.5×10^{-28}	0.75×10^{-28}
Same for 180° direction	0.35×10^{-28}	0.70×10^{-28}
Total cross section for producing photons, assuming spherical symmetry, in cm^2		1×10^{-27}

C. Nucleon Isobars (Excited Nucleons)

In this process it is assumed that in the proton-nucleon collision one of the nucleons becomes excited and then subsequently loses its excitation through photon emission. If it is assumed that in the coordinate system in which the isobar is at rest the photons are mono-energetic, or at least have an energy spread narrow compared to the observed spread shown in Fig. 5, this possibility may also be ruled out by the following considerations. Analysis of Fig. 5 shows that the energy

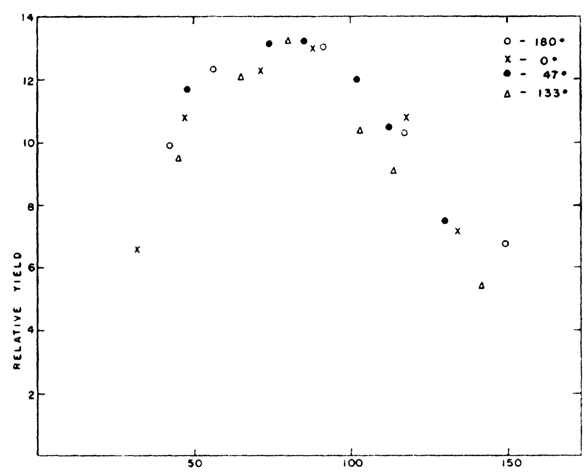

FIG. 5. Energy distributions transformed to system with $\beta=0.32$ in direction of protons.

of the excited state would in this case be about 80 Mev. Figure 3 shows that 40-Mev photons are observed in the forward (0°) direction. This requires that there be isobars moving in a direction opposite to that of the bombarding proton with a velocity of 0.6c. This can only happen if there are nucleons in the nucleus with momenta corresponding to energies in excess of 250 Mev.*

D. Excited State of a π-Meson

This possibility is not completely excluded, if the lifetime of the excited level is sufficiently short. However, the threshold occurring for available energy values below 200 Mev does not agree well with the mass of π-meson plus the mass equivalent of an 80-Mev photon.

E. Neutral Mesons

In this process it is assumed that the proton nucleon collision results in the production of a neutral meson which then decays into two photons. Such a process has been suggested by Lewis, Oppenheimer, and Wouthuysen[6] as a possible origin of the soft component in cosmic radiation.

On the basis of this assumption, the observations lead to mass of about 300 electron masses for the neutral meson involved. A particle of this type, with a half-life of less than 10^{-11} sec., fits all of our present observations. Since this particle is so light compared to a proton, velocities of 0.8c in the center of momentum system of the collision are allowed, and hence the broad distribution of photon energies may be explained. The apparent threshold near 175 Mev and the rapid rise in yield from 175 Mev to 350 Mev is also about what would be expected for this process, and the yield at 340 Mev is the same order of magnitude as the meson yield at this energy. Calculations by Taylor[13] and Marshak[14] of the expected photon spectra from this process are very similar to those observed.** The neutral meson hypothesis is also in agreement, as is also the isobar hypothesis, with the experimental observation that the energy of the peak of the photon spectrum occurs at approximately the same value, independent of the proton energy, when transformed to the proper coordinate system.

The existence of a neutral meson is clearly not required at the present stage of the experiments, but is the only one of the above five hypotheses which seems to fit the experimental data.

A planned experiment to determine whether the photons are emitted singly or in pairs will distinguish clearly between D and E, as well as between C and E.

VI. EXPERIMENTS IN PREPARATION

Several significant experimental tests are clearly implied by the foregoing results and discussion.

1. A liquid hydrogen target experiment is considered to determine a threshold without the uncertainties due to the momenta of nucleons in nuclei. This will also give the *p-p* collision yield, to be compared with the mixture of *p-p* and *p-n* collision yields from other light nuclei.
2. A specifically designed pair counter is in design with which more precise energy and angle distributions can be obtained in reasonable counting periods. From such measurements better information on the proper photon energy spectrum can be obtained, with consequent improvement of information about the existence and mass of an intermediate particle, and better data on absolute yield.
3. A cloud-chamber experimental program has been started, in cooperation with Dr. E. Hayward, seeking the answer about whether the photons are emitted singly or in pairs.
4. Simple experiments geometrically defining the region of emission of the photons have already shown the lifetime of any intermediate particle to be $<10^{-11}$ sec. This type of experiment will be improved.

VII. ACKNOWLEDGMENTS

The authors wish to express their appreciation of the stimulating interest of Professor E. O. Lawrence, and of the cooperation of the cyclotron crew under James Vale and the electronics staff under H. D. Farnsworth.

This work was done under the auspices of the AEC.

* The essential idea here is that the struck nucleon acts independently of the others present, except that it has considerable kinetic energy due to its being bound. See for instance R. Serber, Phys. Rev. 72, 1114 (1947) and M. L. Goldberger, Phys. Rev. 74, 1269 (1948).

[13] T. Taylor (private communication).

[14] R. E. Marshak (private communication).

** It may be noted that the energy distribution of the hypothetical neutral mesons could be calculated from better data of the type given in Fig. 5.