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Photoproduction of mesons and hyperons

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PHOTOPRODUCTION of MESONS and HYPERONS

The availability in recent years of increasingly energetic photon beams from particle accelerators has led to significant advances in the study of *photon-nucleon interactions* and the photoproduction of mesons and hyperons. *This work also holds the* promise of future contributions to better understanding of the nature of the strong interactions.

By R. F. Bacher

Pions, heavy mesons, and hyperons were all first observed in cosmic-ray interactions many years ago. Considering the rarity of the observed events and the difficulty of the experiments, an extraordinary amount of knowledge was obtained from this work. The rate of discovery of new particles and of excited states of particle systems increased rapidly with the development of high-energy accelerators for protons and electrons, and the pace has now been very fast for several years. This report concerns some of the work in one section of the field, the photoproduction of mesons and hyperons.

These photoproduction processes have provided some important information. The existence of neutral pions was first demonstrated by photoproduction. Photoproduction of pions played a significant part in establishing the first pion-nucleon resonance. Since the electromagnetic interaction is relatively weak and is well known, the strong interactions of the particles in the final state can be studied under fairly simple conditions. The interaction of these particles in the final state has large effects on the cross sections and on the angular distribution of the emergent particles; these effects are shown particularly in the photoproduction of pions. Also, since the electromagnetic interaction is relatively weak, proton accelerators have so far proved more effective in providing beams of unstable particles. As a consequence, most of the properties of the unstable particles have been obtained from experiments carried out with proton synchrotrons. The new electron accelerators, both linear and circular, may, with their greater energy and intensity, be able to provide comparable beams of unstable particles as well as a capability to study photoproduction processes.

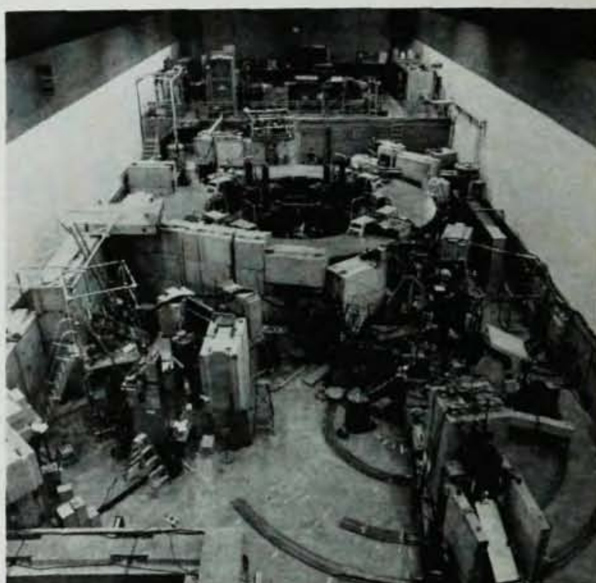

Fig. 1. Experimental area at the Caltech synchrotron. The experimental arrangements are similar to those in several other laboratories.

Electrons, accelerated to high energy either in a circular machine or in a linear accelerator, interact with any target to produce a continuous photon spectrum (bremsstrahlung) which, for electrons of some hundreds of million electron volts energy, is mostly contained in a small cone in the direction of the radiating electrons. It is thus convenient to produce the photon beam inside a cir-

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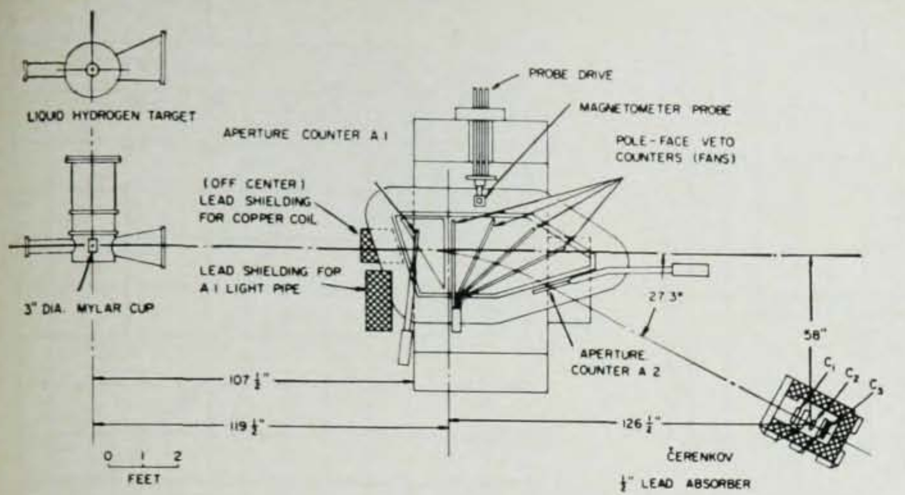

Fig. 2. Liquid-hydrogen target, analyzing magnet, and counters (vertical section)

cular machine and to conduct experiments with the photon beam at some distance from the accelerator. A common experimental arrangement with an electron accelerator is shown in Figs. 1 and 2.

The photon spectrum produced by a monoenergetic beam of electrons has been calculated carefully, including additional corrections which must be made for heavy-element targets customarily used experimentally. The intensity from a thin target is almost inversely proportional to the photon energy and falls rapidly to zero at the energy of the incident electrons. The photon spectrum depends on the target thickness, and because of the consequences of electron scattering in the target it also depends on the radiation cone that is accepted by the beam collimators. For a thicker target, the spectrum varies considerably off the axis of the photon beam, but even for a thin target these angular differences must be taken into account. The expected and observed photon spectra for 485-MeV electrons are shown in Fig. 3 and the agreement is quite good. The principal differences are probably due to the resolution of the detecting equipment.

The most fundamental processes to be investigated are those in which an incident photon interacts with a nucleon, without the influence of other nucleons. For the proton, a hydrogen target (usually liquid hydrogen) is used. For the neutron, liquid deuterium is usually used, and, of course, there is the effect of the proton. Since hydrogen and deuterium are simple nuclei, they have been employed as the targets in most photoproduction studies, although there are many interesting problems in the interactions of photons with heavier nuclei.

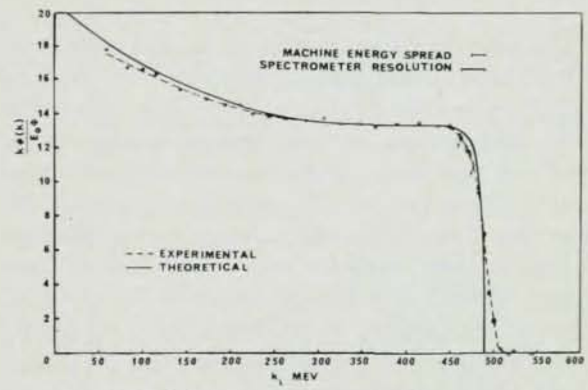

Fig. 3. Calculated and observed photon spectrum from 485-MeV electrons

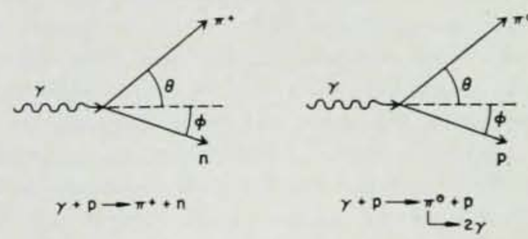

Fig. 4. Photoproduction of positive and neutral pions from the proton

Photoproduction of pions

The first photoproduction of mesons was observed in 1949 by McMillan, Peterson, and White soon after the completion of the first synchrotron. These first observations of charged pions were made with a beryllium target, but soon hydrogen targets were being used to obtain more significant data. For hydrogen, the photoproduction of a single pion is the lowest-energy phenomenon observed that is typical of strongly interacting particles. With a hydrogen target, both π^+ and π^0 mesons can be produced in simple two-body reactions (see Fig. 4).

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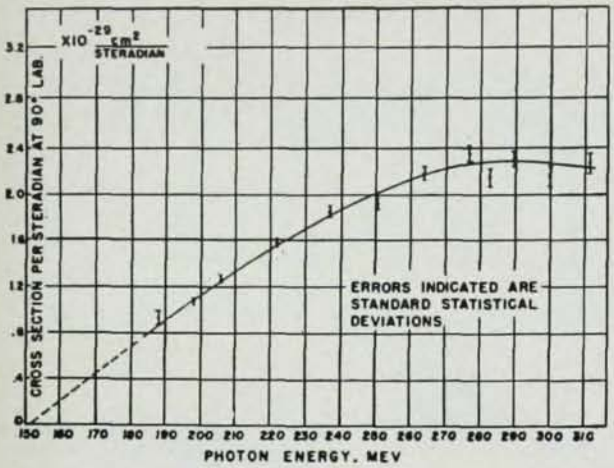

Fig. 5. Differential cross section for the photoproduction of positive pions from hydrogen as observed by Steinberger and Bishop

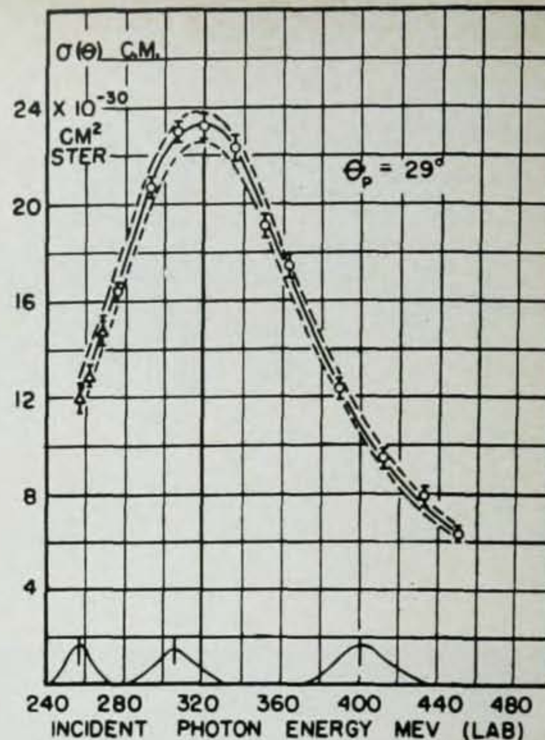

Fig. 6. Differential cross section for neutral-pion photoproduction at 115° c-of-m (29°, lab) from hydrogen showing strong peak at 320 MeV

The neutral pions produced in the second reaction shown decay very rapidly into two photons with a mean life of 1.7×10^{-16} sec. Since the pion, proton, and neutron masses are known, it would be possible to determine the unknown kinematic properties of the emergent particles by observing either the angle, energy, or momentum of one of these particles for a particular photon energy. With a continuous spectrum of photons, however, this energy is not known. It is possible, by observing the angle and momentum or energy of one of the emergent particles, to determine the other angle and momentum completely, as well as the energy of the incident photon. To be certain of the interpretation, it is desirable to have, as a check, more observed information than the necessary minimum. In a very beautiful experiment, Steinberger, Panofsky, and Stellar investigated this reaction with photon energies ranging up to about 300 MeV, and for the first time demonstrated the existence of the neutral pion, which had been inferred from cosmic-ray experiments. They detected the two gamma rays produced by neutral pion decay. By observing both photons at various production angles, they were able to determine that two, and only two, photons were produced, and that both were correlated with the production of a neutral pion which decayed in flight. As expected, the energetic photons from the pion decay disappeared below a threshold of about 150 MeV.

In the study of such a reaction, one wishes to know the differential cross section as a function of the energy of the incident photon and the angle of the emergent pion. To determine the cross section, one must know not only the kinematics of a single reaction but also the number of photons in some energy range and the efficiency of the counters used. Accurate determinations of the number of incident photons are not quite as easy as one might think; they have been achieved by knowing the spectrum from the target and the energy in the photon beam during the experiment. The total energy is customarily measured by a quantometer (developed and calibrated by Robert Wilson) which produces a shower from the incident photons and measures the total ionization.

The first determination of the cross section for the photoproduction of mesons that was reasonably accurate and extended over a considerable energy range was made by Steinberger and Bishop for positive mesons. They observed the range of the positive pions produced at 90° and thus determined both angle and energy. Pions were distinguished from other particles by detecting the positrons produced in the delayed decay chain. The differential cross section, as shown in Fig. 5, was observed to increase approximately linearly and then flatten out in the region from about 260 to 310 MeV—the highest photon energy then available. It was also observed that the angular distribution near 90° was rather flat.

Measurement of the cross section for the photoproduction of neutral pions is more difficult because it is necessary to determine the counter

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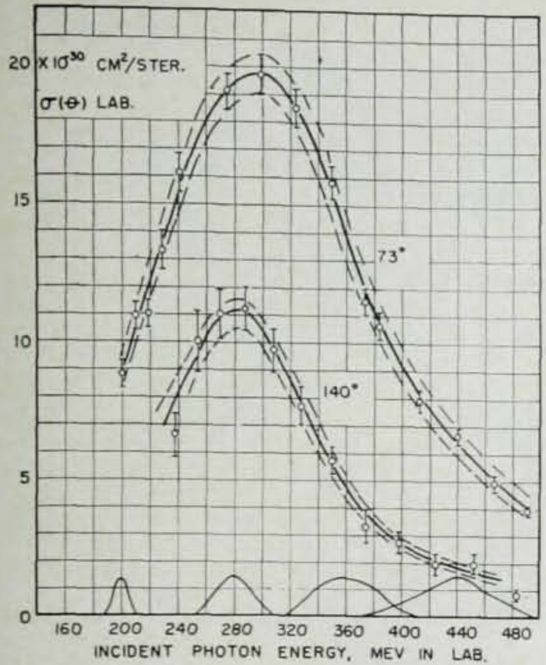

Fig. 7. Differential cross section for photoproduction of positive pions from hydrogen for laboratory angles for the pions of 73° and 140° as observed by Walker, Teasdale, Peterson, and Vette

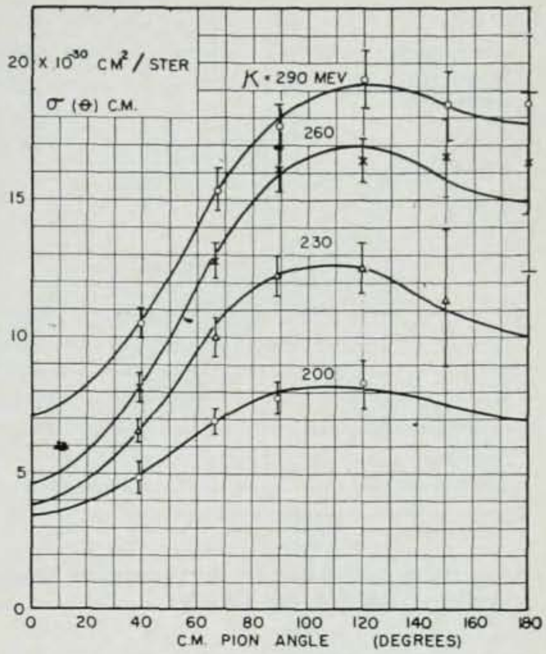

Fig. 8. Angular distribution for positive-pion photoproduction at 200, 230, 260, and 290 MeV

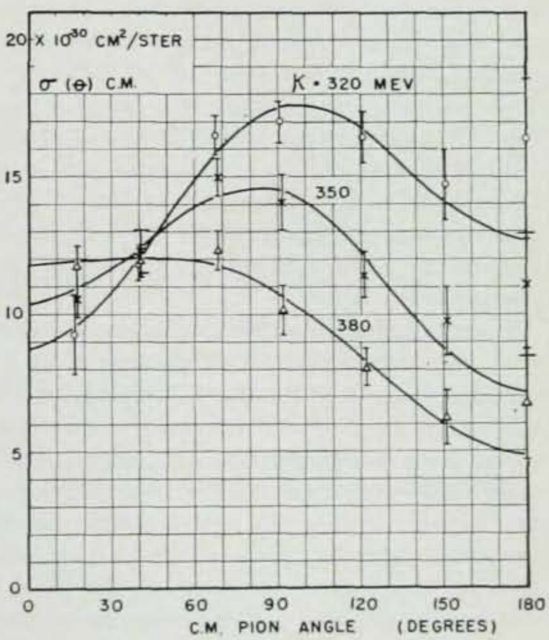

Fig. 9. Angular distribution for positive-pion photoproduction at 320, 350, and 380 MeV

efficiency for the decay photons. When these measurements were made it was found that the cross sections for the photoproduction of positive and neutral pions were roughly comparable, but near threshold the cross section for neutral-pion production increased more gradually than for positive pions.

Before long it was possible to extend the photoproduction measurements to higher energy. Walker, Tollestrup, and others at Caltech first observed that the cross section for the photoproduction of both neutral and positive pions from hydrogen does not flatten out at higher photon energy but decreases rapidly above 300 MeV to produce a strong peak in the excitation curves. They observed a decay photon from the neutral pion in coincidence with the recoil proton. It is possible, of course, to observe only the recoil proton and to measure its momentum and angle of recoil—a good method if no protons come from other reactions. Some higher-resolution results were soon obtained in this way (see Fig. 6).

For photoproduction of positive pions the easiest method is to observe the angle and momentum or energy of the pion. Figure 7 shows the excitation curves for two different angles. The peak in the cross section is pronounced and occurs at 300 MeV; the cross section is much reduced in the backward direction. Some angular-distribution curves for increasing photon energy are shown in Fig. 8. At the lowest photon energy (200 MeV), the angular distribution is quite flat, while just below the peak at 300 MeV it shows greater emission in the backward direction. Figure 9 shows the angular distribution for a photon energy near the maximum cross section and the peak in the angular distribution is near 90°. For higher en-

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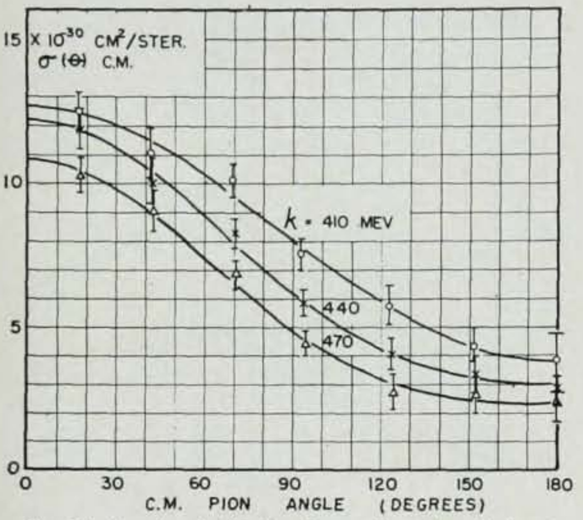

Fig. 10. Angular distribution for positive-pion photoproduction at 410, 440, and 470 MeV

ergy well above the 300-MeV maximum, the angular distribution in Fig. 10 is peaked in the forward direction. These observations, combined with pion scattering data and the predictions of Brueckner and Watson, established the first pion-nucleon resonance, often referred to as an isobaric state. This pion-nucleon system with angular momentum 3/2 and isotopic spin 3/2 has total mass of 1238 MeV and quickly decays into a pion and a nucleon. It is now sometimes called Δ (1238), fits into the same SU (3) multiplet with the newly discovered Ω^-, and is regarded as just as much a particle as the Ω^-.

For photons below 300 MeV, the reactions we have considered in which only one pion is produced are quite adequate to account for the observations. As expected, no negative pions are observed with a hydrogen target. Above about 300 MeV it becomes energetically possible to produce two pions and thus the interpretation of the observations becomes more difficult. It is possible, however, by careful selection of the pion angle and momentum for a given endpoint of the photon spectrum, to distinguish single-pion production from multipion processes.

As the investigations of single-pion photoproduction were extended to higher energy at Cornell and at Caltech, further resonances were found. These are not as prominent as the first resonance and have not yet been investigated with as high energy resolution. Figure 11 shows the total cross section from just above the first resonance to more than 1.3 BeV for the photoproduction of positive pions from hydrogen. There is a second reso-

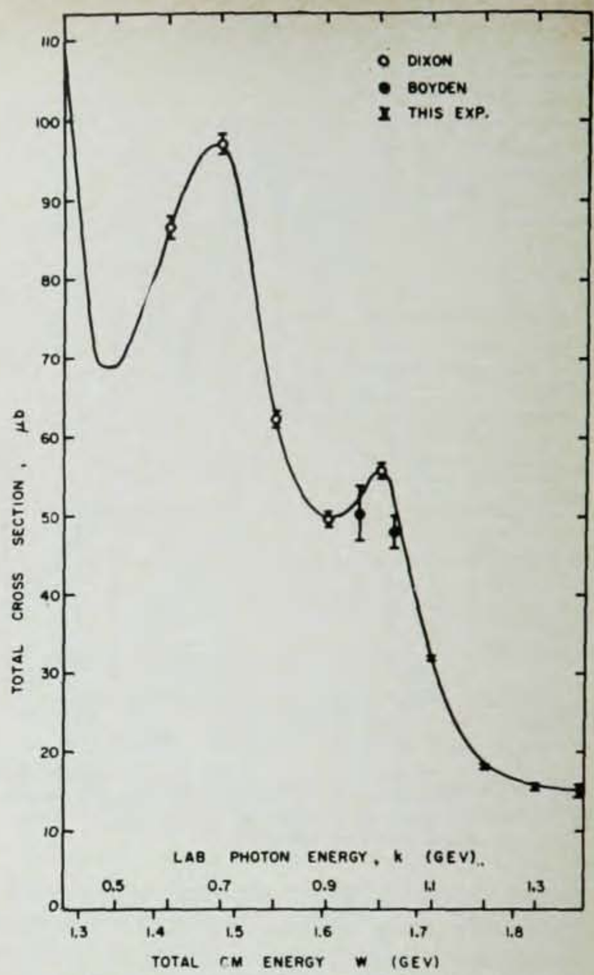

Fig. 11. Total cross section for positive-pion photoproduction as observed by Dixon, Boyden, Kilner, and Walker

nance at about 700 MeV and a third resonance at about 1.0 BeV.

The photoproduction of neutral pions has also been investigated at higher energies, and one finds that it also shows higher resonances. The higher resonances are less clear for neutral than for positive pions, and the cross sections are lower by a factor of two or three. This is ascribed principally to the fact that these states both have isotopic spin ½. For all three resonances the observed peaks for positive-pion production are at slightly lower energy than for neutral pions.

If the photoproduction of single pions is studied at small angles, some interesting results appear. Early work showed only that the cross section for positive-pion production increased in the forward direction above 400 MeV, but the observations were not carried to angles less than about 30° in the center-of-momentum system. At small angles, the number of positrons which accompany the pions is very large, and it has been difficult to distinguish positive pions in such a mixture. Below the first resonance there is no increase in cross sections at small angles. Figure 12 shows

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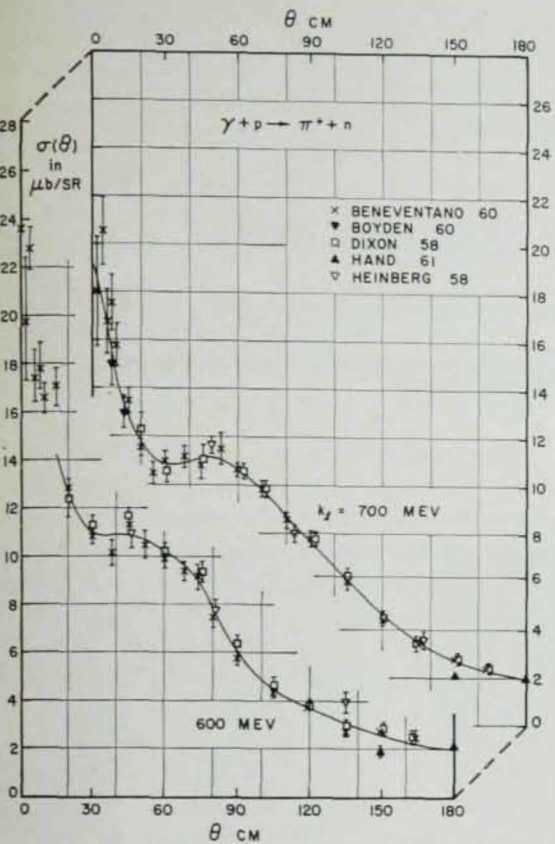

Fig. 12. Angular distribution for positive-pion photoproduction showing rapid increase at small angles

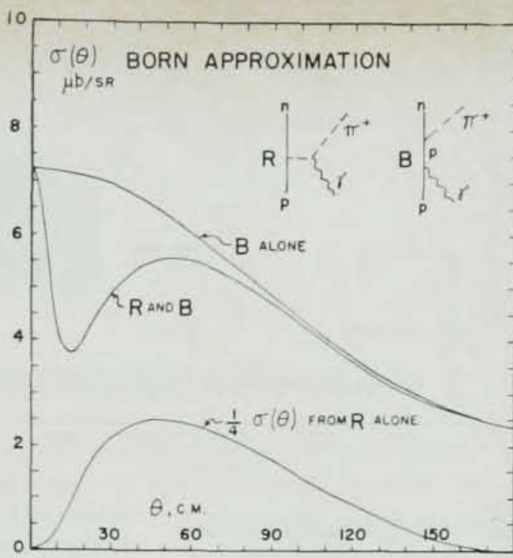

Fig. 13. Born approximation for positive-pion photoproduction

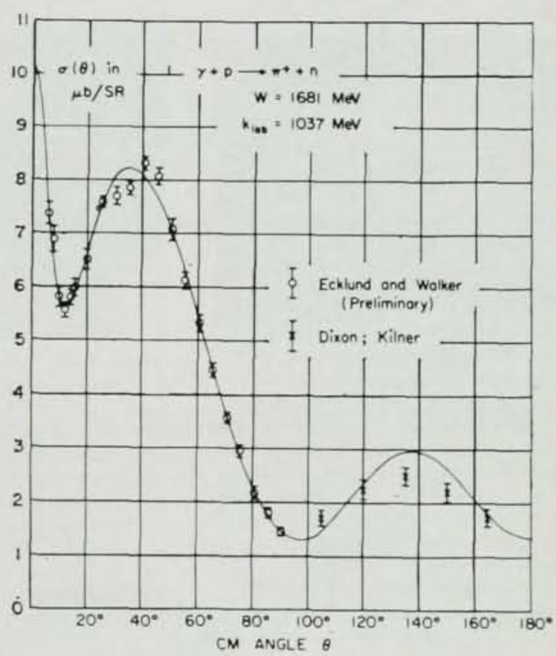

Fig. 14. Angular distribution for positive-pion photoproduction at 1037 MeV showing Moravcsik fit

the positive-pion results occuring at 600 and 700 MeV. The peaking in the forward direction is strong, and at 700 MeV there is some evidence of a minimum around 30°. The rapid variation of cross section with angle at small angles is to be expected if some sort of interference effect is present in meson photoproduction. If one tries to account for this angular variation by analysis into a series of terms in powers of $\cos\theta$, it is found that, even using terms of the sixth order, no adequate fit is obtained.

A method of analysis which looks into the nature of the pion-nucleon interaction has been proposed by Moravcsik and is generally used. This recognizes that a principal contribution to the cross section for charged-pion production comes from the interaction of the photon with the meson current. This contribution to the cross section, which is variously called the meson-current, photoelectric, or retardation term, is proportional to $[(\sin^2\theta)/(1-\beta\cos\theta)]^2$, where β is the meson velocity. Figure 13 shows the diagram R associated with this interaction and the cross section plotted as a function of pion angle. The term R goes to zero at 0° and 180° and has a pole at the unphysical angle defined by $\cos\theta = 1/\beta$. The direct interaction of the photon with the proton is shown in diagram B. The individual cross-section plots are not really meaningful, but the two together, which are the Born approximation, produce by interference the rather spectacular result of a minimum in the cross section at small angle.

Moravcsik has pointed out that since essentially all theories proposed for meson production contain this pole term, one should take it into account explicitly by expanding $(1-\beta\cos\theta)^2\sigma(\theta)$ in a power series of $\cos\theta$. Figure 14 shows the cross

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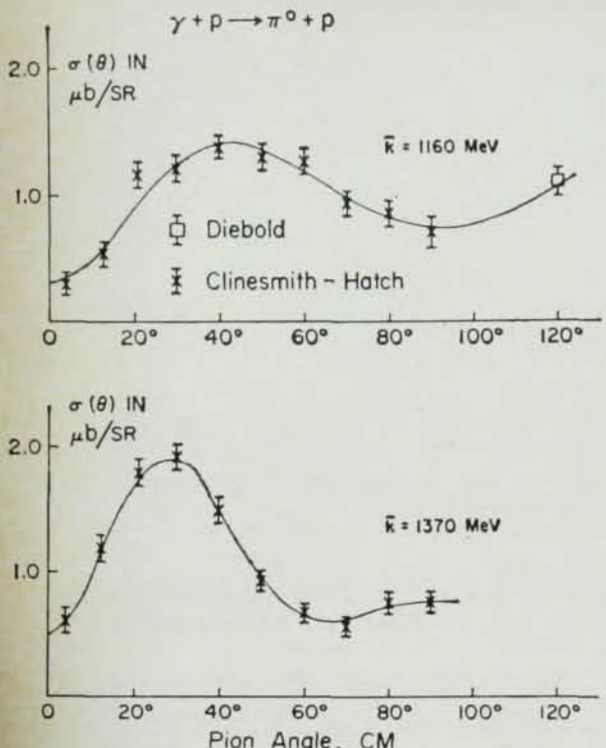

Fig. 15. Angular distribution for neutral-pion photoproduction at 1160 and 1370 MeV

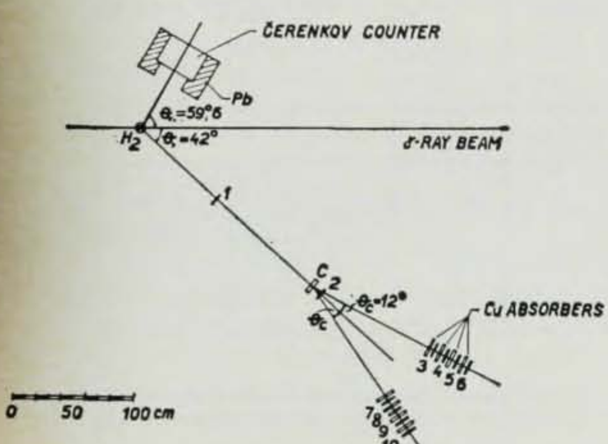

Fig. 16. Experimental arrangement used by Frascati group to determine proton polarization in neutral-pion photoproduction

section for single π^+ production at 1037 MeV. The curve is a Moravcsik fit with terms in cos θ up to the sixth order. At small angles, the data are well accounted for by the Born approximation. It is possible to extrapolate the data to cos $\theta = 1/\beta$ and, from the residue obtained at the pole, to get a value for the nucleon-coupling constant. While this extrapolation depends critically on the accuracy of the data, it does give a value for the coupling constant which is in general agreement with the accepted value $g^2/4\pi \simeq 15$.

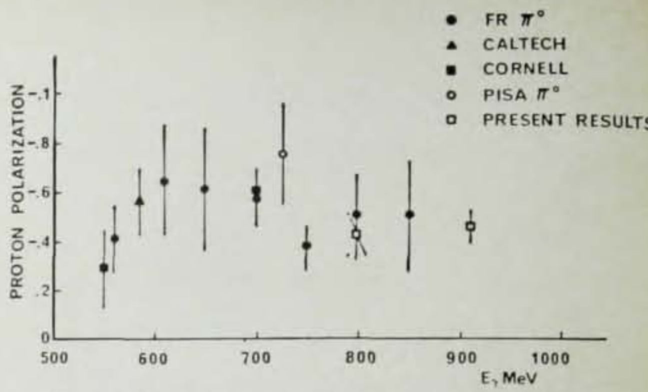

Fig. 17. Proton polarization observed in neutral-pion photoproduction

The photoproduction of single neutral pions from hydrogen at small angles is studied most easily by observing both photons produced by the decay of the neutral pion, since this allows one to work right down to zero degrees for the angle of pion emission. The cross section near 0° decreases rapidly with increasing photon energy. At approximately 1 BeV, the differential cross section for single neutral-pion photoproduction is a fraction of a microbarn in comparison to the positive-pion cross section of nearly 10 microbarns. Figure 15 shows the angular distribution of neutral pions at 1160 and 1370 MeV. Although the data cannot be fitted properly with a power series in cos θ, it is possible to do so using a Moravcsik fit with a pole term for a particle of mass about 800 MeV (corresponding to a ρ or an ω) and including powers of cos θ up to the sixth order. Present data are deficient at large angles and any more definite conclusions are not possible.

It was first pointed out by Sakurai that a study of the polarization of the proton in the neutral-pion photoproduction in the energy region from 500 to 1000 MeV could give some interesting and critical information about the nature of the second and third resonances. The experiments have been carried out at several laboratories by somewhat different experimental procedures. Figure 16 shows the experimental arrangement used by Mencuccini, Querzoli, and Salvini at Frascati. They have counted γ-rays from neutral-pion decays in coincidence with protons scattered from carbon. Two proton energies, corresponding to two initial photon energies, are counted simultaneously. From the known analyzing power for carbon it is possible to determine the polarization of the protons by observing their left-right asymmetry.

Figure 17 shows the Frascati results and those from several other laboratories. The protons are

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Report from

BELL LABORATORIES

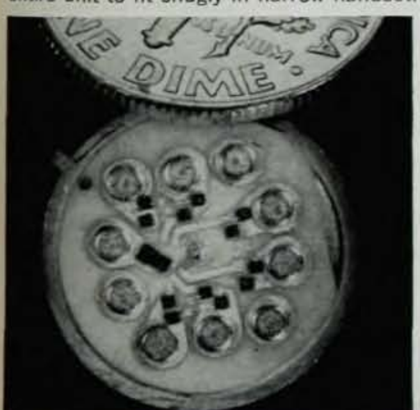
New circuits for communications

The success of a modern large-scale communications system depends importantly on the circuits of which it is built. For this reason Bell Telephone Laboratories places great emphasis on exploring new approaches to high-performance, economical circuit design. The circuits illustrated below are but a few examples of recent Bell Laboratories developments that are helping to advance the techniques of communications.

Bell Telephone Laboratories

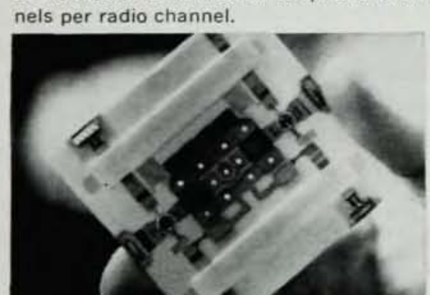
Research and Development Unit of the Bell System

Circuit for mounting inside telephone handset for use by people with impaired hearing. Circuit includes one PNP transistor, provides up to 25 db gain, and has negative feedback for stability and to compensate for variations in component characteristics. Power is derived by taking a small part of direct current supplied to the telephone transmitter. Circuit board is flexible to permit part of conducting path to be bent and entire unit to fit snugly in narrow handset.

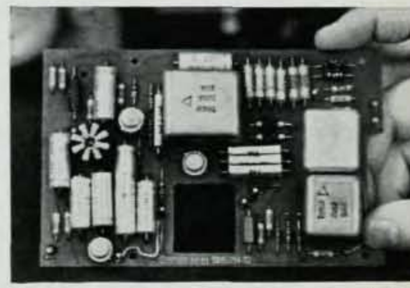


High-speed integrated logic package consists of 3 separate flip-flop circuits assembled together on a single header. On the 11-lead ceramic header, all circuit interconnections are made using gold thermocompression bond wires. This device contains 6 transistors (2 are required for each flip-flop) and 12 resistors. The individual flip-flops perform their switching functions with typical operating times of approximately 6 nanoseconds.

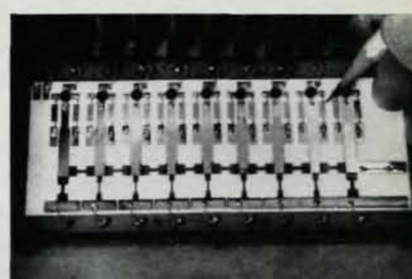
Parametric amplifier used in new microwave radio system will provide low-noise amplification to a radio frequency signal which is frequency-modulated by 1200 telephone conversations. It is a reflection type parametric amplifier operating in the 4-gigacycle range, providing approximately 13 db of gain using a varactor diode pumped at approximately 12 gigacycles. Its very low noise figure, typically 3.5 db, permits increased systems capabilities which are used to increase the number of telephone channels per radio channel.



Integrated balanced microwave amplifier makes use of high-frequency germanium transistors for precise wideband applications. Each stage of amplifier (one stage shown) consists of a pair of electrically similar transistors whose inputs and outputs are combined by 3-db couplers. This arrangement eliminates tuning adjustments and provides excellent gain flatness and impedance matching. Multistage amplifiers of this type have been designed to operate with bandwidths of 1000 mc in the 0.5- to 3-gigacycle range, with noise figures of about 6 db.



Compressor circuit used in several telephone carrier systems raises volume of soft voice sounds and lowers volume of loud voice sounds. This new circuit effects a 2-to-1 reduction in dynamic range of a telephone signal, which is then transmitted with an improved signal-to-noise ratio. Nearly perfect compression is achieved over greater than the normal voice range, as a result of circuitry that varies the impedance of two precise silicon diodes. A 3-stage feedback transistor amplifier maintains desired stability and provides the required transmission characteristics.



Thin-film decoder for high-speed pulse code modulation systems converts binary pulse sequences into analog signals. Circuit consists of precision resistor network and multiply-encapsulated control diodes. Precision resistors (pointer) generate reference currents that are switched into resistive ladder network (I-shaped elements at bottom of unit). Output voltage is proportional to binary code applied to diodes. Precision sufficient for decoding 9-digit binary codes is obtained, at code rates up to 12 mc (108 mb/s pulse rates).

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definitely polarized throughout the energy region from 550 to more than 900 MeV and there are no large changes in this polarization near the 700-MeV resonance. The existence of polarization of the protons at 90° in the center-of-momentum system in the energy region from 500 to 700 MeV is evidence of interference between the first and second states of the pion-nucleon system and indicates that they have different parity.

Similarly, the polarization of the protons corresponding to photon energies above the second state indicates that the second and third resonances have opposite parity. The first state is known to be a p state of even parity from the nature of the angular distributions of photoproduction and from the pion-proton scattering. The second state is therefore of negative parity and the third of positive.

Table 1 gives the quantum numbers now associated with these three pion-nucleon states (first suggested by Ronald Peierls). The mass values ob-

Table 1

State	l_π	P	I	k_{lab} (MeV)
N* [Δ (1238), 3/2 +]	P	+	3/2	~ 325
N** [N (1517), 3/2 −]	D	−	1/2	~ 700
N***[N (1692), 5/2 +]	F	+	1/2	~1000

tained from an analysis of the resonances in neutral-pion photoproduction agree reasonably well with those obtained from the analysis of pion-nucleon scattering. It is to be expected from an analysis of the resonances that the positive-pion photoproduction peaks should be at lower energies than those for neutral pions. The differences can be calculated and agree reasonably well with observations. The isotopic spin of both second and third states is ½, as mentioned before; the assignment of J and l have been made by study of the angular distributions and of the most likely states of the system which would lead to such distributions. The observations of the second and third states agree generally with expectations from these quantum-number assignments, but the experimental data are not sufficiently precise to be sure that these states are not more complicated.

The threshold for photoproduction of two pions is at 322 MeV. This is close to the dominant first resonance due to the isobaric state $I=3/2$, $J=3/2$, and two-pion production is negligible compared to single-pion production in the region immediately above the threshold. The photo reaction with hydrogen leading to a positive pion, a negative pion, and a proton has been investi-

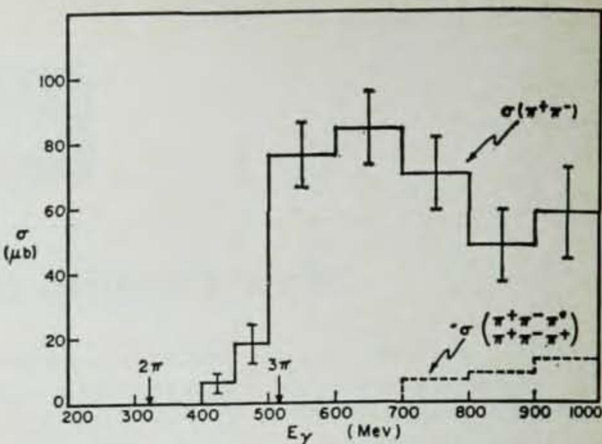

Fig. 18. Total cross section for two- and three-pion photoproduction

gated by Chasan, Coconni, and others at Cornell using a hydrogen diffusion cloud chamber. Their results are shown in Fig. 18. They find that the total cross section is very low just above threshold and rises rapidly around 500 MeV, reaching a peak of about 80 microbarns around 600 MeV and then falling gradually. The cross section for three-pion photoproduction, which has a threshold of 516 MeV for the photon in the laboratory system, is very small up to about 700 MeV and is from 5 to 10 microbarns up to 1000 MeV. They also find that there is a significant difference in the direction of emission of the π^+ and π^-, the angular distribution of the π^- being peaked in the forward direction but not that of the π^+.

Drell at Stanford proposed that for peripheral interactions of high-energy photons the preferred reaction is to produce a pion at a small angle to the photon beam and a virtual pion which interacts with the proton. The proton-pion system may go to a number of final states depending on the energy available. Figure 19 shows the diagram for this reaction with a final state of proton and π^+. At the correct energy, the effect of the 3/2, 3/2 isobar should be apparent. Walker and others have obtained some experimental results, determining the photon energy by subtraction of

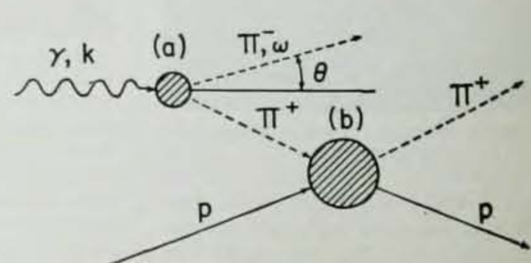

Fig. 19. Diagram for two-pion production by the Drell process

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numbers of negative pions observed with a photon end point of 1200 MeV from those observed with an end point of 1300 MeV. Figure 20 shows their results. There is a maximum for total negative-pion energy ω near 480 MeV. This corresponds to total kinetic energy Q in the pion-nucleon system of approximately 150 MeV, which is the Q for the isobaric state corresponding to a total energy of 1238 MeV. The expected yield for the statistical model is much smaller and shows no maximum. More recent calculations show more complete agreement with the experimental results. The Drell effect is expected to enhance production in the forward direction of pions (and other particles also) in the new high-energy electron accelerators.

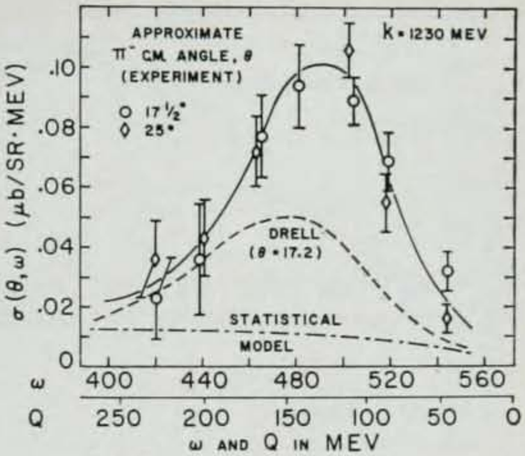

Fig. 20. Negative-pion photoproduction at 1230 MeV showing the Drell effect

Photoproduction of other mesons

There are several heavier mesons which should be produced by photons of 900 to 1200 MeV incident on protons. In order of increasing mass, there is, first, the K meson of 496 MeV, which has strangeness +1 and is produced in conjunction with the Λ or Σ hyperons. These photoproduction processes have been observed and we shall return to them shortly.

Next in mass is the η meson at 548 MeV. The η has strangeness 0, isotopic spin 0, and angular momentum 0. It has been observed in a number of other particle reactions and decays to two photons like a neutral pion, to a neutral pion and two photons, to three pions, or to two pions and a photon. The mean life is not known, but the η must be partially stable since the observed half width is less than 10 MeV in energy. The photoproduction of the η meson should be observed in a manner similar to neutral-pion production except for the complexities of its decay. It has, however, taken very careful searching among the multipion photoproduction data to detect its presence. Salvini, Querzoli, and others at Frascati have observed photoproduction of η mesons by means similar to those used for neutral pions. They have also been able to distinguish some of the different decay modes, but the differential cross section for photoproduction, observing all decay modes, is less than a microbarn per steradian and only a few tenths of a microbarn for any given mode. This is much less than single-pion production, and as a consequence only this fragmentary information is available now.

Next heavier among the mesons are the ρ and the ω which are well known from various reactions among strongly interacting particles. Both the ρ and ω should be produced by photons in much the same way that pions are produced, but photon energies in excess of 1 BeV are required. The ω is a charge singlet $I = 0$, with angular momentum $J = 1$, and negative parity. Since it is a vector meson it would be of interest to investigate its role in the strong interaction by photoproduction, but it has proved elusive. Attempts to detect its photoproduction have not met with clear success; probably the ω-nucleon coupling constant is relatively small. Further attempts at somewhat higher energy are needed and will probably be carried out soon.

The ρ meson is a charge triplet $I = 1$, with angular momentum $J = 1$, and negative parity. Neutral ρ^0 mesons have been protoproduced from the proton by Franklin, Silverman, and others at Cornell, and that process is interesting to study in order to determine the role of the ρ meson in strong interactions. The reactions which are pertinent here are shown below.

$$\gamma + p \rightarrow p + \pi^+ + \pi^- \qquad (1)$$

$$\gamma + p \rightarrow p + \rho^0 \qquad (2)$$
$$\rightarrow p + \pi^+ + \pi^-$$

$$\gamma + p \rightarrow N^{*++}\ (3/2, 3/2) + \pi^- \qquad (3)$$
$$\rightarrow p + \pi^+ + \pi^-$$

First, there is the two-pion photoproduction, which is well known, to form a general background in the BeV region. Next is the ρ^0, which may appear as a two-body final state. From the observation of one of the decay pions and the proton, it is possible to determine the invariant mass of the pion-pion system and to ascertain that the ρ^0 plays an important role in two-pion production. The third process, the photoproduction of the dominant isobaric state and a negative pion, we discussed earlier. It is possible to minimize the latter effect by selecting the appropriate photon energy and observing positive pions in coincidence with protons.

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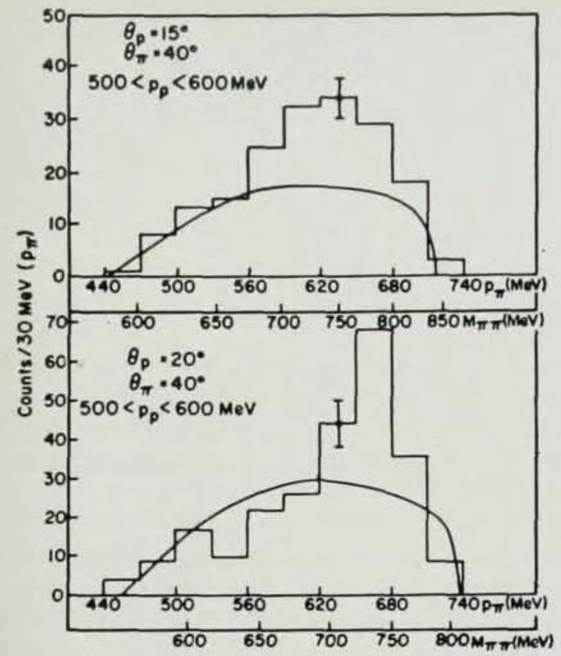

Fig. 21. Neutral-rho photoproduction observed by *Silverman and others at Cornell*

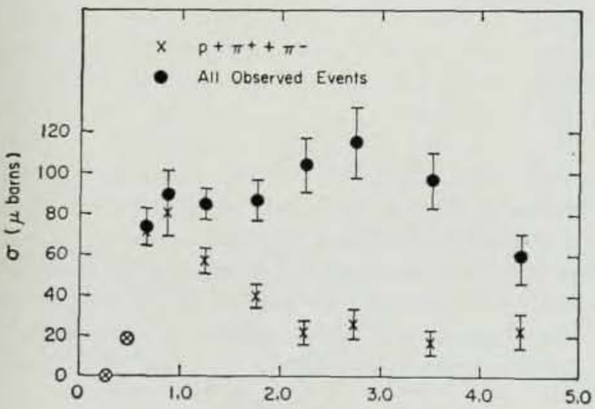

Fig. 22. Total cross section for multipion photoproduction up to 4.5 BeV from bubble-chamber observations at the Cambridge Electron Accelerator

Figure 21 shows that the ρ^0's are preferentially produced over the general two-pion background at a mass for two pions of about 750 MeV—the expected value. Some differential cross sections have been found; these are about 4 microbarns per steradian for emission of the ρ^0 at 60° in the center-of-momentum system, and they fall off for larger and smaller angles.

Photoproduction processes recently have been extended to nearly 5 BeV in experiments at the Cambridge Electron Accelerator. Multipion production has been studied with a 12-inch hydrogen bubble chamber in a magnetic field and a photon beam of greatly reduced intensity. Observations were confined to interactions in which there were three or more emergent tracks. Neutral particles could be deduced from the analysis of the observed tracks, but reactions with two or more neutral particles in addition might not be distinguished. Figure 22 shows the total cross section for two-pion photoproduction and for all multipion processes observed. The cross section for two-pion production rises rapidly at about 700 MeV and then drops above 1 BeV. The total cross section for multipion processes remains relatively high, the largest above 1 BeV being the photoproduction of two or three charged pions along with one or more neutral pions.

As expected, there is strong evidence for the isobaric state N^* (3/2, 3/2) in the two-pion photoproduction up to about 1.2 BeV and the positive pion is preferentially associated with the proton after the reaction. This state still accounts for about a third of the photoproduction for photons between 1.2 and 1.8 BeV.

The photoproduction of ρ^0 mesons which disintegrate into two pions is an important process above a photon energy of 1.4 BeV and is the dominant feature above 1.8 BeV. It is likely that some interesting results may come from further study of this reaction. No real evidence for the photoproduction of ω^0 mesons is found in the photoproduction of three pions and this is in strong contrast to observations of ρ, which shows clearly in three-pion-decay products.

The photoproduction of single pions from the proton has been studied in the new energy range at Cambridge with counters to detect the emergent particles. Primary attention has been given to the photoproduction of single neutral pions. Figure 23 shows the experimental arrangement. The gamma rays from the photoproduction products in the hydrogen target are detected in the Cerenkov counter in the short arm. The protons are deflected magnetically to determine their momentum and their time of flight measured to aid in the discrimination against charged pions. The long arm is nearly twenty meters long. Even with such powerful equipment for analysis, there are difficulties in separating the protons of single-pion production from those associated with multipion production above 2 BeV.

It has, however, been possible to determine that the cross section near 90° in the center-of-momentum system for single neutral pions decreases by nearly a factor of 100 as the incident photon energy increases from 2 to 4 BeV. Pion production at smaller angles is much greater, and for a given

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angle neutral-pion production is significantly larger than positive-pion production. Resonances for photons in the range of 1.5 to 2.5 BeV, expected from previous observations of pions incident upon protons, do not show large effects. There is some evidence for two new pion-nucleon resonances at photon energies of 2.9 and 3.5 BeV. A sharp increase in the low-energy gammas in coincidence with protons may be a result of a pronounced increase in η^0 production at 3.5 BeV. It is clear that there is a great deal of information in the multi-BeV photoproduction of pions, ρ's, ω's, and η's which is now known only in fragmentary form and which may be helpful in unraveling the role of these particles in the strong interactions.

Photoproduction of hyperons

I would like to return briefly to the photoproduction of K mesons mentioned earlier. No K mesons have been observed in the interaction of photons with protons until the maximum photon energy has been increased above the threshold for production of a K^+ and a Λ. This reaction has a threshold at 911 MeV and is considerably above the threshold for which K mesons could be observed if they were produced with nucleons. The initial system, which is made up of the photon and the proton with which it acts, has hypercharge +1, and this quantity is conserved in the reaction; hence the K^+ with hypercharge −1 must be produced in association with a baryon of hypercharge +2. The photoproduction of K's with Λ's and at somewhat higher energy with Σ's has been studied at Caltech, Cornell, Frascati, and most recently at higher energy at the Cambridge Electron Accelerator.

The various photoproduction reactions are:

$$\gamma + p \rightarrow K^+ + \Lambda \quad (1)$$
$$\gamma + p \rightarrow K^+ + \Sigma^0 \quad (2)$$
$$\gamma + p \rightarrow K^0 + \Sigma^+ \quad (3)$$

$$\gamma + n \rightarrow K^0 + \Lambda^0 \quad (4)$$
$$\gamma + n \rightarrow K^0 + \Sigma^0 \quad (5)$$
$$\gamma + n \rightarrow K^+ + \Sigma^- \quad (6)$$

The Σ's are a charge triplet with a somewhat higher rest mass than the Λ and thus appear at higher photon energies. The first photoproduction of strange particles was observed in reaction 1 and most of the work so far has been done on reactions 1 and 2. The K's, Λ's, and Σ's are all unstable and this complicates the observations. There is the usual difficulty of observing reactions from the neutron and, in particular, those reactions in which all products are neutral.

The study of reactions 1 and 2 is difficult because for each K meson there are several hundred pions. Various means have been used to detect the K mesons: magnetic analysis, pulse height in scintillation counters, time of flight, and the presence or absence of Cerenkov radiation. It has proved to be most effective to use several of these methods in order to get better discrimination. The best resolution has been obtained by Anderson, McDaniel, and others at Cornell, as shown in Fig. 24. They have used specific ionization, minimum range, Cerenkov radiation from the pions, and a very effective time-of-flight measurement. The latter utilizes the bunching of the electrons in the synchrotron and measures the phase of the arriving

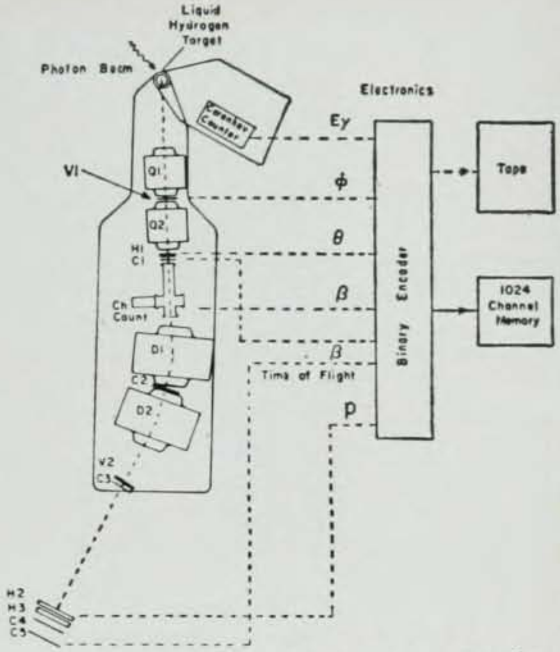

Fig. 23. Experimental arrangement for counter observation of pion photoproduction at Cambridge

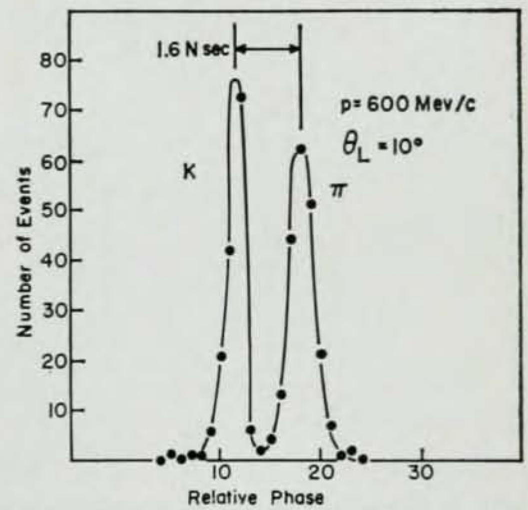

Fig. 24. Resolution of pions from K mesons as observed at Cornell

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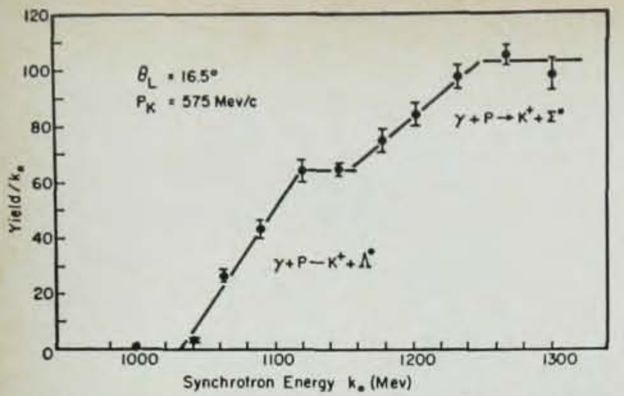

Fig. 25. Excitation curve observed by Anderson, McDaniel, et al. showing photoproduction of lambda and neutral sigma hyperons

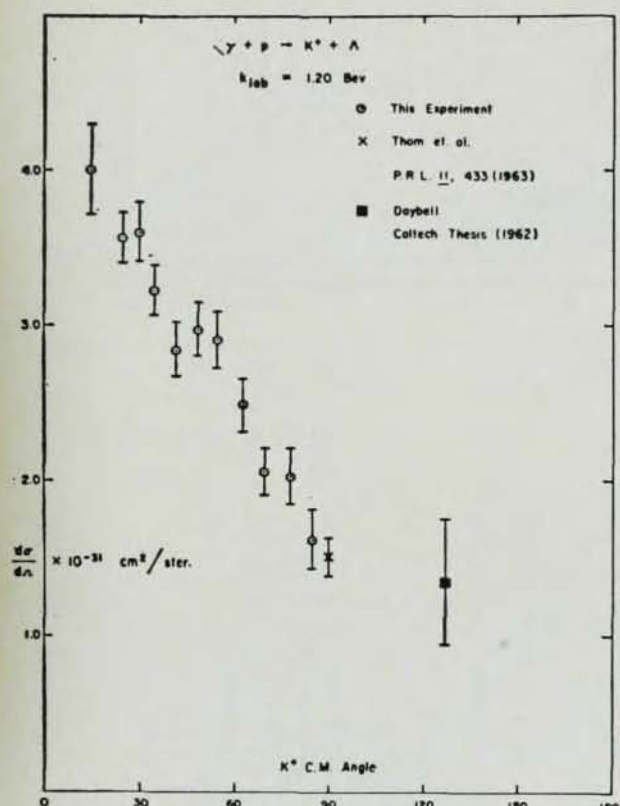

Fig. 26. Angular distribution for positive-K and lambda photoproduction as observed at 1.2 BeV by Thom and others at Cornell and Keck and Daybell at Caltech

K mesons relative to that of the electrons at the accelerating cavity of the synchrotron. They achieved almost complete separation of K's and π's with a time-of-flight difference of 1.6 nanosec.

Figure 25 shows an excitation curve for K mesons observed for increasing maximum synchrotron energy. As the maximum photon energy was increased, the yield of K mesons increased first because of Λ production and then again at higher energy as the Σ reaction contributed. The determination of the differential cross section from these studies indicates that near threshold for the production of Λ's the angular distribution is quite isotropic in the center-of-momentum system. Also, the differential cross section increases linearly with the K momentum. These observations are consistent with *s*-wave photoproduction of the K mesons. Above 1 BeV the cross section starts to show some peaking in the forward direction, indicating the presence of higher partial waves. This is also indicated by the observed polarization of the Λ found at 90°. Figure 26 gives the angular distribution at 1200 MeV. There is a pronounced peaking in the forward direction, which is only accounted for satisfactorily by the inclusion of second-order terms in the cosine of the K-meson angle.

It may be expected that the exchange of a K meson in photoproduction may play a similar role to the exchange of a pion at lower energy. So far, the photoproduction data for K mesons have not been sufficiently detailed and accurate to determine the $KN\Lambda$ coupling constant. It does appear, however, that the magnitude of the K-meson photoproduction is smaller near threshold than would be expected.

The photoproduction of K mesons in association with Σ's has been observed, but there are only a few results which permit the determination of cross sections. Some preliminary results on the photoproduction of K mesons with neutral Σ's have been obtained at Cornell; these indicate that the differential cross section at small angles is smaller than at 90°.

Some interesting preliminary observations have been made at higher energy using a hydrogen bubble chamber at the Cambridge Electron Accelerator. Evidence has been found for the fact that several reactions involving K's, Λ's, and Σ's show resonances which might be expected from earlier data on K^- interactions observed with K-meson beams. In particular, the excited state Y_1^* (1385) and Y_0^* (1520) are evident even from preliminary data. It is clear that there will be some interesting results from this work at higher energy.

In these past years some rather critical information has come from the photoproduction experiments. Current-day instrumentation is much more sophisticated than that of a few years ago and it will be possible in the future to use the available photon beams of increased intensity and energy to find further information about the nature of the interaction of these strongly interacting particles. This new work is just starting to give interesting information and we can look forward to many new and exciting results in the near future.

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