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Photoproduction of π^0 Mesons from Protons*

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The yield of π^0 mesons from gamma rays on protons has been measured as a function of center-of-mass angle for gamma-ray energies from 170 Mev to 340 Mev. The results are shown to be consistent with a model of production predominantly through a $J=\frac{3}{2}$, isotopic spin, $\frac{3}{2}$, state, which is resonant at about 300 Mev gamma-ray energy. There is evidence for S-state production and possibly electric quadrupole, P-wave production through the resonant state.

I. INTRODUCTION

THE production of neutral mesons by photons was first observed by Panofsky *et al.*[1] Later experments were done by others[2–5] which showed that the excitation curve for gamma rays less than 300 Mev agreed with a cross section $\sigma \sim p^3$, where p is the meson center-of-mass momentum, and that the angular distribution in the center of mass behaved roughly as $d\sigma/d\Omega \sim 2+3\sin^2\theta$.

In addition, the California Institute of Technology group[6] found that the cross section went through a maximum at about 300 Mev and decreased markedly for greater energies in a manner reminiscent of resonant interactions. The purpose of this experiment was to measure this process in more detail.

An explanation of the process was examined by a "strong coupling" theory based on a resonant state of the nucleon.[7,8] Theoretical descriptions of the process have been given in terms of partial waves through intermediate states.[9,10] Watson[11] and Aizu[12] have derived the formal relationship between the photoproduction and scattering of mesons. Ross[13] has developed a semiphenomenological description by calculating the photoproduction of mesons in perturbation theory and adding the experimentally known scattering. Chew and Salzman[14] have calculated meson photoproduction directly using a cutoff theory which has given agreement with scattering experiments.

II. EXPERIMENTAL PROCEDURE

The experimental data was acquired in two runs. The gamma-ray beam from the Massachusetts Institute of Technology electron synchrotron was passed through a high-pressure hydrogen tank and emulsions were placed around the beam to pick up the recoil protons from the π^0-meson production process. The layout is shown in Fig. 1. The gamma-ray beam passed through a defining collimator and two protecting collimators into the tank through a $\frac{1}{4}$-in. aluminum window and out a $\frac{1}{2}$-in. aluminum window. Two four-inch lead walls screened the emulsions from particles coming directly from the windows. The end plates of the tank could be removed to give access into the tank: there was an additional port with provision for electrical leads for thermocouples. A fiber board "dark room" was set up at one end of the tank for loading and unloading the emulsions. These were mounted on an aluminum circle which was slipped into place at the center of the tank. There was a thin wall integrating ionization chamber[15] upstream from the tank and a thick-walled chamber downstream, both for monitoring purposes. Around the outside of the tank was a container for a dry-ice and alcohol mixture.

If nuclear emulsions are exposed for several minutes to hydrogen at room temperatures the hydrogen will reduce the AgBr such that the plate, when developed, will be impossibly blackened. The temperature coefficient of this reaction is such that, at a temperature of −60°C, a week's exposure to hydrogen at 40 atmospheres gives no perceptible blackening. For this reason the gas tank was cooled by a mixture of dry ice and methyl alcohol. This treatment did not appear to diminish the sensitivity of the plates for our purposes.

Figure 2 shows the angle in the laboratory system and range in nuclear emulsion for the π^0 recoil proton for various gamma-ray energies and meson center-of-mass angle, θ. It is evident that the proton angle and range is markedly asymmetric with respect to meson angle. A systematic error of 1° in proton angle would change the predicted gamma-ray energy by 10 Mev for cos-

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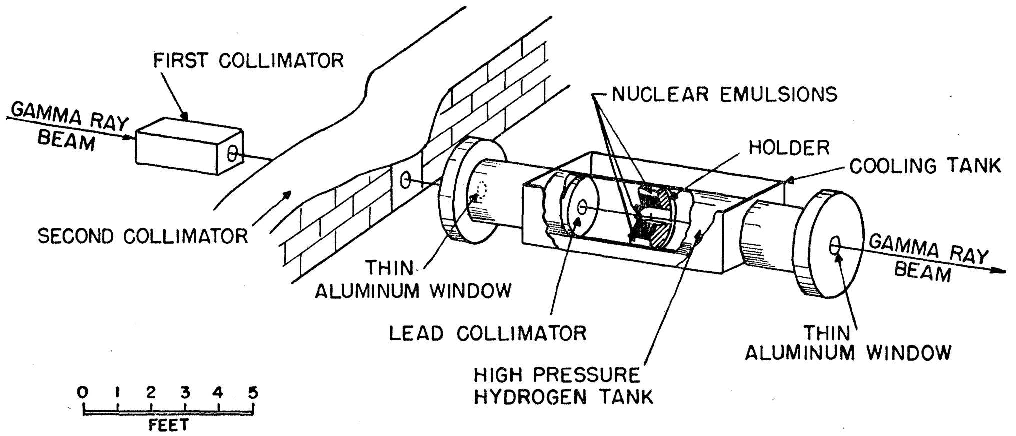

FIG. 1. Schematic of the exposure arrangement, showing the passage of the gamma-ray beam through the hydrogen tank and the placement of the plates.

$\theta = 0.7$ and 2 Mev for $\cos\theta = -0.07$. An error in proton energy of 10 percent would change the center-of-mass angle 3° for $\cos\theta = -0.7$ and 1° for $\cos\theta = 0.7$. Since the excitation curve was expected to be varying rapidly with energy we wished to avoid errors that would distort the angular distribution or excitation curve. This was one reason that all proton energies were measured by their range rather than by grain counting. In order to stop the protons the detecting emulsion consisted of 6 pellicles (4 in the first run) stacked onto a glass backed emulsion. The protons were tracked through from pellicle to pellicle. The stack of emulsions were glued together with Krylon. The stack was mounted with clips onto a Bakelite support which was mounted in turn to the aluminum ring that fitted into the tank. When in place, the angle between the plane including the beam and the surface of the emulsion was 22°. The protons came into the stack at a relatively grazing angle which insured that over 90 percent of the protons would stop in the stack.

The tank and collimators were aligned with respect to the beam. The plates were inserted into the tank and the tank evacuated. The tank was cooled by the dry ice and methyl alcohol mixture and then flushed with hydrogen several times. The hydrogen was passed over activated charcoal at liquid air temperatures for purification in the second run. During the run the temperature of the gas was measured at various points in the tank; the mean temperature was −65°. The synchrotron was run at an electron energy of 320 Mev for run 1 and 355 Mev for run 2 as calibrated by magnetic field measurements. This agreed within 5 Mev of the energy calculated by noting the cut-off in energy of the proton recoils from the π^0 production.

After the run the emulsion stacks were removed and a set of x-ray marks passed through them as reference points. The pellicles were separated by dipping the stack for a few minutes in acetone. The pellicles were developed by the hot-cold method with the hot bath ($\sim$20°C) at less than usual temperature to underdevelop the emulsions so that they would effectively cut off tracks of particles with energy greater than $\frac{1}{5}$ rest mass energy. The pellicles were shrunk to original size after washing by addition of alcohol to a water bath and deposited on fixed 25 micron plates.

The secondary beam monitors were calibrated by using a shower-integrating ionization chamber placed through a stack of lead.[15] This calibrating scheme has yielded cross sections which have been consistently higher by a factor of about 1.5 compared to other laboratories. By using a portable ion chamber, an intercalibration was performed with the Cornell Synchrotron and the Illinois Betatron laboratories which indeed showed this same factor. In this paper we will quote cross sections based on the calibrations of these laboratories since they find mutual agreement. This will have

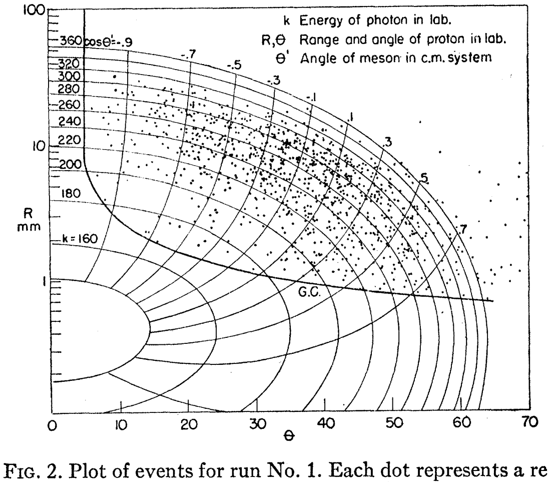

FIG. 2. Plot of events for run No. 1. Each dot represents a recoil proton plotted with respect to its angle in the laboratory system and its range in nuclear emulsion. The superimposed lines give the energy of the photon responsible and the cosine of the meson center-of-mass angle. The line labelled G.C. gives the lower limit to observe recoils because of insufficient range in the gas to get to the plates. The points occurring outside of the π^0 plot are mainly photoprotons from impurities in the gas.

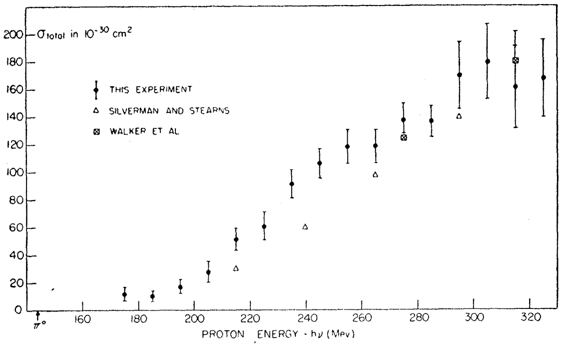

FIG. 3. The total cross section for $\gamma+p\rightarrow\pi^0+p$. The other points refer to the work in references 2 and 6.

the merit of allowing intercomparison with their cross sections. The discrepancy remains unexplained.

The gas was spectroscopically analyzed for impurities. For run 1 there were 0.5 percent and run 2, 0.3 percent impurities by volume, mainly O_2 and N_2.

III. THE DATA

The top pellicle of a stack was scanned for all proton tracks whose dip into the emulsion would correspond to a particle coming from the beam. The number of tracks not meeting this condition was about 10 percent of the total. Each track was traced through the stack to its ending. In some cases the track left the stack or suffered a nuclear collision; in such a case, grain counting gave its residual range. Each track was entered into a plot similar to Fig. 2, which shows the total results of the first run.

The kinematics of the π^0 reaction demanded that all protons be emitted at angles less than 64°. The protons found at angles greater than this were attributed to lower energy interactions with the nuclei of the impurities. The measurement of photoprotons from a 300-Mev bremsstrahlung beam on compound nuclei has been measured by other experimenters.[16–18] The number of protons we obtained agreed with the yields predicted from these results and the amount of impurities found in the hydrogen. From the measured angular distributions, we could predict the background protons found at angles less than 90° from those found at angles greater than 90°. It would be possible to get recoil protons from the nuclear Compton effect or from n-p or p-p collisions from neutrons and protons in the beam produced by materials upstream or downstream. In the first case, if one supposed the reaction cross section to be equal to the nucleon Thompson cross section, which seems reasonable experimentally,[19,20] this would give a contribution of 1 percent to the protons observed. These protons would fall in the angular interval 0° to 90° and if this effect were present we would find a proton contribution, after background subtraction, in the 64° to 90° interval. For the latter effect, calculations from known cross sections indicate a contribution of 2 percent, and an angular distribution radically different from that found in the 90° to 180° hemisphere. Following the subtraction due to impurities we obtain an effect from these sources equal to 3±3 percent of the proton contribution from the π^0 reaction.

We estimate that the angle measurement of each track deviated from true with a mean square spread of 2.5°. This corresponds to an average energy resolution over all angles of about 10 Mev. The scanning involved less than 5 percent loss of tracks over-all. The possibility of missing the high-energy protons because of thin tracks was checked by scanning lower pellicles in the stack where the now lower-energy protons gave a clear track in pellicles with less general background. This correction amounted to about 30 percent at the highest energy. The total number of tracks recorded was about 1700. The reaction kinematics computed to get the diagram of Fig. 2 was done by assuming the mass of the π^0 meson to be 136 Mev. A more recent determination of the π^+, π^0 mass difference by Chinowsky and Steinberger[21] does not affect our results significantly. The line labeled G.C. in Fig. 2 shows the limitations in energy and angle of this detecting scheme. The line drawn across the bottom of the figure corresponds to the limit of protons energetic enough to traverse the gas to the emulsions. In addition, the lead protectors masked protons making an angle less than 8° with the beam.

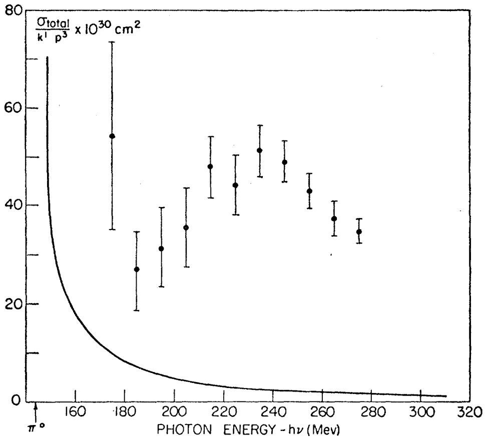

FIG. 4. Plot of $\sigma(\text{total})/k'p^3$. k' and p are the photon and meson momenta in the center-of-mass system in π^0 rest mass units. This number would be a constant near threshold for P-wave meson emission. The curve shown is the S-wave cross section expected from an electric dipole interaction with the proton plus charge exchange production.

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[16] H. Levinthal and A. Silverman, Phys. Rev. **82**, 822 (1951).

[17] R. Littauer and J. Keck, Phys. Rev. **86**, 105 (1952).

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[19] A. Silverman (private communication). The nuclear Compton effect was measured to be less than 5 times Thompson cross section.

[20] Pugh, Frisch, and Gomez, Phys. Rev. **95**, 590 (1954).

[21] W. Chinowsky and J. Steinberger, Phys. Rev. **93**, 586 (1954).

TABLE I. Summary of experimental data.

Photon energy	A_0^0	A_1^0	A_2^0	A_2^+		$A_0^0+(5/3)A_2^0$
				Cal. Tech.[a]	Cornell[b]	
220	6.7±0.5	−2.5±1.3	− 5.9±2.2	−5.1	− 3.2±2.0	− 2.9±3.6
250	12.5±1.2	−2.0±2.3	− 7.8±4.3	−7.5	− 7.5±1.8	− 0.5±6.5
270	13 ±1.2	−2.0±1.5	− 8 ±3.5	−8.4	−11.4±2.0	− 1.9±5.5
290	18.3±1.3	−1.5±1.5	−17.4±3.1	−8.4		−11 ±4.5
320	17.3±1.4	+0.9±2.0	−10.7±4.0	−6.5		− 0.8±6.8

[a] See references 22 and 23.
[b] See reference 24.

IV. RESULTS

The total number of tracks in each energy interval was counted and the total cross section computed. A correction has to be applied since the full angular range is not quite observed. This is done by extrapolating the measured angular distribution assuming no higher power of $\cos\theta$ than $\cos^2\theta$. The lowest energy point (175 Mev) is computed by using the extrapolated front to back ratio which we measure at higher energies. The results are plotted in Fig. 3 with the results of other experiments,[2,6] where their differential cross sections have been reduced to total cross sections, by using our measured angular distribution. The behavior of the curve with energy is shown in Fig. 4 by plotting $\sigma/k'p^3$ against photon laboratory energy. p is the meson momentum and k' the photon energy in the center-of-mass system both being measured in π^0-meson mass units. One would expect a constant for this number near threshold; however, our points are well above threshold.

The tracks were divided into five energy intervals for an analysis of angular distribution. A least-squares fit to the formula

$$d\sigma/d\Omega = A_0^0 + A_1^0 \cos\theta + A_2^0 \cos^2\theta$$

was made. The results are shown in Table I.[22–24] From these coefficients a front-to-back ratio was computed and is plotted in Fig. 5.

V. DISCUSSION

If we allow all possible electromagnetic interaction leading to emitted mesons in angular momentum states $l \leq 1$, the angular distribution, which gives three parameters $(A_0^0 A_1^0 A_2^0)$, would not allow computation of the eight parameters (4 complex transition matrix elements) to describe the process. Watson's formalism shows that the phase angle of these matrix elements is given by the scattering phase shift so, with these given, we have 8 real numbers to be found which give the electromagnetic transition element through either a $\frac{3}{2}$ or $\frac{1}{2}$ isotopic spin state. In addition we can relate the π^+ to π^0 cross sections, giving then 6 numbers to calculate 8 unknowns. This is possible with π^+ and π^0 mesons from protons since the so called "recoil" terms appear in the isotopic spin, $\frac{1}{2}$, matrix with the same sign and relative magnitude. If we can use the threshold energy dependence to separate S and P states, we would have 8 numbers. Our experimental errors forbid such a project and we will confine our arguments to an analysis which assumes the largest contribution to come from a $P_{\frac{3}{2}}$ state.

On the above assumption, it is shown below that the total cross section is almost wholly a measure of the magnetic-dipole, $J=\frac{3}{2}$ interaction. The behavior with energy is not in general disagreement with models assuming a resonant interaction in this state. On Fig. 4 we have plotted a curve showing the contribution to the total cross section if we assumed an S-wave contribution through an electric dipole interaction with the proton plus charge exchange scattering of the π^+ meson in the S state; this contribution is below what we can observe.

The front to back ratio being less than one is an indication of the admixture of a different parity state

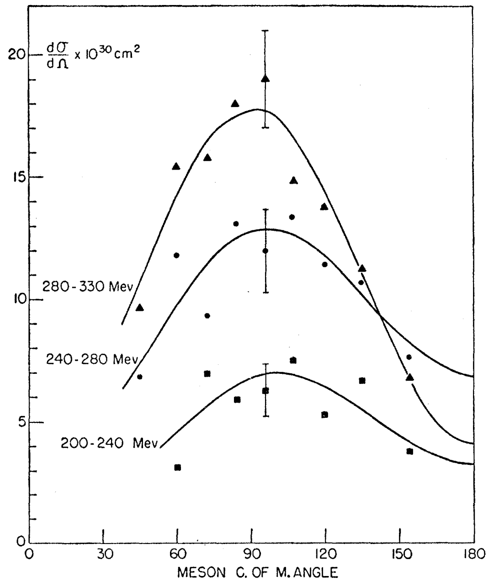

FIG. 5. Angular distribution of π^0 mesons in the center-of-mass system for three different energy intervals. A typical error (standard deviation) is shown on one point of each curve. The solid lines are the best fit to the expansion $d\sigma = A_0 + A_1 \cos\theta + A_2 \cos^2\theta$.

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[22] Walker, Teasdale, Peterson, Vette, and Oakley (private communication).

[23] Tollestrup, Keck, and Worlock (private communication).

[24] Jenkins, Luckey, Palfrey, and Wilson, Phys. Rev. **95**, 179 (1954).

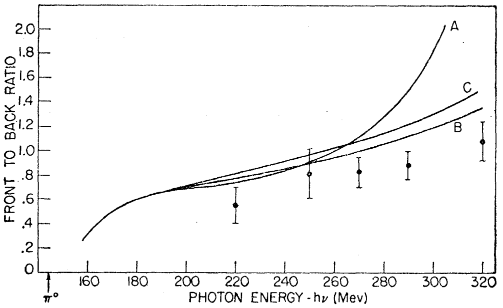

FIG. 6. Measured ratio of mesons produced in the forward hemisphere to back hemisphere in the center-of-mass system. The solid curves are taken from Watson's paper. They give the front to back ratio assuming predominant production in the $J=\frac{3}{2}$, $I=\frac{3}{2}$ state with S-wave production through an electric-dipole interaction with the proton and charge exchange production. The three curves are calculated then by assuming (A) Fermi-Metropolis (see reference 25), (B) Glicksman (see reference 26), (C) Martin scattering phase shifts (see reference 27).

and it seems logical to assume this an S state. Figure 6 shows that this asymmetry is consistent with Watson's formalism which explains the S state by the sum of charge exchange scattering and direct π^0 S-wave production through the proton dipole moment. It can be seen that our experiment favors those scattering phase shifts[25–27] where α_{33} goes thorugh 90° and the other P phase shifts are small. We may estimate the amount of S state by using this formalism and assuming that the interference between S and P terms is dominated by the $P_{\frac{3}{2}}$ scattering phase shift, α_{33}, (using Watson's notation):

$$\begin{aligned} d\sigma(\text{interference}) &\sim 2\,\mathrm{Im}(A^*C)\cos\theta \\ &\sim 2|A|\,|C|\cos\alpha_{33}\cos\theta, \end{aligned}$$

where $|A|$ and $|C|$ are proportional to the absolute values of the S and P matrix elements for electromagnetic production. Using the α_{33} of reference 26, we obtain

$$\sigma_{\text{total}}(S\text{ wave}) = (4\pm3)\times10^{-30}\text{ cm}^2$$

as an average between photon energies from 200 Mev to 300 Mev. This is about 3 percent of the total π^0 cross section. It is about 4 percent of the total π^+ S-wave cross section. The latter is obtained by assuming the main π^0 P-wave contribution to be through an isotopic spin $\frac{3}{2}$ state and therefore

$$\sigma^+(S\text{ wave}) \simeq \sigma^+ - \tfrac{1}{2}\sigma^0.$$

The amount of S-wave expected from an electric dipole interaction with the proton would be about $(\mu/M)^2$ times the π^+ S wave, where μ and M are the meson and nucleon mass respectively. This factor is 2 percent. In addition we expect charge exchange scattering proportional to $|\alpha_1-\alpha_3|^2$ which is of the same order of magnitude. α_1 and α_3 are the S-wave scattering phase shifts for isotopic spins $\frac{1}{2}$ and $\frac{3}{2}$ respectively.

Column 5 of Table I gives the number $A_0+(5/3)A_2$ which would be 0 for the magnetic dipole, $P_{\frac{3}{2}}$, term,

$$d\sigma \sim 5-3\cos^2\theta = 2+3\sin^2\theta.$$

It cannot be said that this experiment clearly proves a deviation from this behavior. However, there could be several explanations for departure from this angular distribution. We assume meson states of $l\leq1$ which is reasonable since the effect appears at low energies. One could have a magnetic dipole interaction leading to a $P_{\frac{1}{2}}$ state or an electric quardupole leading to a $P_{\frac{3}{2}}$ state. Experimentally these would be qualitatively distinguished, in the first case, by a rapid change in angular distribution as the scattering phase shifts in the $P_{\frac{3}{2}}$ and $P_{\frac{1}{2}}$ states changed with respect to one another and thereby changed the interference term. In the second case, if the interaction occurred through the main $\frac{3}{2}$, $\frac{3}{2}$ state the interference term would be independent of the phase shift, and the change in angular distribution would occur through the, presumably, slower changes in the electromagnetic transition elements. The slim evidence given here allows no choice between the two. It is of interest to calculate the contribution of electric quadrupole transitions to explain our results. Using Watson's notation,

$$\begin{aligned} d\sigma &\sim \tfrac{1}{2}|C|^2(5-3\cos^2\theta)+\tfrac{1}{2}\,\mathrm{Im}(E^*C)(3\cos^2\theta-1) \\ &\qquad +\tfrac{1}{8}|E|^2(1+\cos^2\theta) \\ &= \tfrac{1}{2}|C|^2(5-3\cos^2\theta)\pm\tfrac{1}{2}|E|\,|C|\,(3\cos^2\theta-1) \\ &\qquad +\tfrac{1}{8}|E|^2(1+\cos^2\theta), \end{aligned}$$

we obtain as an average from 200 to 340 Mev,

$$|E|/|C| = 0.25\pm0.18.$$

The contribution to the total cross section from the quadrupole term is then 0.5±0.5 percent of the main term, or roughly $(0.5\pm0.5)\times10^{-30}$ cm^2. Preliminary calculations by Chew and Salzman[14] on π^0 photoproduction indicate, on theoretical grounds, an expected quadrupole term of this order of magnitude and sign.

The presence of an additional P-wave term is also expected from the angular distribution of π^+ mesons as measured by the California Institute of Technology groups.[22,23] At high energies (400 Mev) they find that the coefficient of the $\cos^2\theta$ term, A_2^+, becomes positive which would be possible only with another radiative transition, P-wave term. Feld has shown that their results can be described by the addition of the electric quadrupole interaction.

Since there is doubt about the detailed character of the P-wave angular distribution, we cannot analyze the π^+ cross section into a P- and S-wave contribution uniquely. However, if all P-wave contributions were through an isotopic spin $\frac{3}{2}$ state the ratio of the $\cos^2\theta$ term in π^0 and π^+ angular distributions would be 2 to 1.

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[25] E. Fermi and N. Metropolis (unpublished).

[26] M. Glicksman, Proceedings of the Fourth Annual Rochester Conference on High Energy Nuclear Physics (University of Rochester, Rochester, 1954).

[27] R. L. Martin, Phys. Rev. 94, 765 (1954).

This coefficient, A_2^+, in the photoproduction of π^+ mesons, as determined at Cornell[24] and the California Institute of Technology,[22,23] is tabulated in Table I. At high energies the ratio of 2 to 1 appears correct. At lower energies the agreement is less satisfactory.

VI. CONCLUSIONS

The behavior of the π^0 photoproduction cross section between gamma-ray energies of 170 Mev and 320 Mev is well fitted by a model with over 90 percent of the production going through a magnetic dipole $J=\frac{3}{2}$, isotopic spin $\frac{3}{2}$, state resonant at about 300 Mev. There is a small amount (3 percent) of S-state production consistent with direct production of π^0 mesons by interaction with the dipole moment of the proton and through charge exchange of charged mesons. The interference of S and P waves is such as to favor the α_{33} scattering phase shift going through 90°. There is a suggestion of another mode of P-wave production, perhaps by electric quadrupole radiation through a $J=\frac{3}{2}$ state or magnetic dipole through a $J=\frac{1}{2}$ state.

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Analysis of a High-Energy Cosmic-Ray Shower. I. Soft Component and Trident Process[*]

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An analysis is presented of the soft component arising from a high energy nuclear shower ($\sim 3\times 10^{13}$ ev) observed in stripped emulsion. The chief results obtained are: (1) The production ratio of neutral π mesons to charged shower particles is 0.50 ± 0.11; (2) the lifetime of the neutral π meson is found to be $(1_{-0.5}^{+1})\times 10^{-14}$ sec; (3) the mean free path for direct electron pair production by high-energy electrons is found to be 4.4 and 1.1 radiation units for electrons in the energy intervals 1 to 10 Bev and 10 to 100 Bev, respectively.

INTRODUCTION

THE event considered in this paper was found in a stack of twenty-four 4 in.×6 in.×400μ G-5 stripped emulsions, packed in direct contact with each other and flown for 8 hours at 102 000 ft at 55° geomagnetic latitude. The emulsions were mounted on glass before development and processed by the usual temperature methods. After development each plate was cut into four 3 in.×2 in. sections for microscopic observation. The emulsion stack was then consecutively mounted and aligned on Lucite frames using heavy nuclei as markers.[1]

The event is of the type $3+36_p$,[2] and was so situated that the shower particles traversed 3.1 cm before leaving the outside edge of the stack; the average path length per emulsion was 2 mm. Of the 36 shower particles emanating directly from the star, 25 formed a narrow cone of half opening angle$=1.08\times 10^{-2}$ radian. Due to the high degree of alignment attained, each individual track could be followed through successive emulsions without any ambiguity (target diagrams were made in each emulsion). After traversing 3.97 mm one of the shower particles underwent a nuclear interaction producing a $0+12_p$ star (I_1) in which two of the secondary particles were in the narrow cone of the original event; one of these was almost exactly in the direction of the particle producing the star I_1 and it made another nuclear interaction of the type $13+16_p(I_2)$ after traversing an additional 24 mm.

The angular distribution of the primary star is plotted in Fig. 1. On the assumption that the primary was a proton, the kinematical energy is found to be $3.7\times 10^4 Mc^2$ using the median angle method[3] and $(3.4_{-2.5}^{+3.5})\times 10^4 Mc^2$ using the statistical method of Castagnoli *et al.*[4]

ENERGY MEASUREMENTS OF VERY HIGH-ENERGY PARTICLES

Due to the very high energy in the soft component produced in this event, the conventional method of measuring the multiple Coulomb scattering fails. However, the high degree of collimation makes possible the measurement of the relative scattering between particles.[5] In this method we measure the relative separation of two tracks and derive the mean second difference ($\bar{D}'_{\rm rel}$) for a fixed cell length t. In this type of

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[*] This research was supported in part by the U. S. Air Force through the Office of Scientific Research of the Air Research and Development Command.

[1] J. Crussard *et al.*, Phys. Rev. **93**, 253 (1954).

[2] This is the notation introduced by the Bristol group; $B+S_p$ means a star with B gray+black prongs ($I/I_0\geq 1.5$) and S shower particles ($I/I_0<1.5$) produced by a singly charged particle (p). The subscript n denotes a neutral primary.

[3] M. F. Kaplon and D. M. Ritson, Phys. Rev. **88**, 386 (1952).

[4] C. Castagnoli *et al.*, Nuovo cimento **10**, 1539 (1953).

[5] Lord, Fainberg, and Schein, Phys. Rev. **80**, 970 (1950).