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Photoproduction of Bosons.

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CONTENTS. —

1. – Introduction.

Pion photoproduction on nucleons has been for many years a powerful means to study the dynamics of strongly interacting particles. Single-pion photoproduction dominates the low-energy region (below 500 MeV). The region above 1 GeV is dominated by the photoproduction of multiple pions, vector bosons and strange particles.

In this paper we will attempt a simple presentation of the most relevant experimental facts about multiple-pion photoproduction together with a presentation of the various theoretical models which have been developed.

We do not claim to present a complete picture of this complex and rapidly changing field. It is also most likely that we have neglected many very important contributions. In particular we have considered only papers published before November 1966.

Double-pion photoproduction becomes kinematically possible above a γ-ray energy of 325 MeV. However, the total cross-section becomes appreciable only above a γ-ray energy of 500 MeV. Above this energy, the formation of an $\mathcal{N}^*(1238)$ resonance between the particles in the final state becomes kinematically possible. In this energy region we can consider many quasi-two-body intermediate states. Focusing our attention on systems with two or three pions in the final state, we have the following possibilities:

TABLE I.

Threshold (GeV)	Intermediate state	Final state
a) 0.54	$\mathcal{N}^*(1238)+\pi$	$\mathcal{N}+2\pi$
b) 0.71	$\mathcal{N}+\eta^0$	$\mathcal{N}+3\pi$
c) 1.05	$\mathcal{N}+\rho^0$	$\mathcal{N}+2\pi$
d) 1.11	$\mathcal{N}+\omega$	$\mathcal{N}+3\pi$
e) 1.66	$\mathcal{N}^*(1238)+\rho^0$	$\mathcal{N}+3\pi$

2. – Double-pion photoproduction.

With a proton target the possible reaction channels are

$$\gamma+p \to p+\pi^+ +\pi^- , \tag{1}$$

$$\gamma+p \to n+\pi^+ +\pi^0 , \tag{2}$$

$$\gamma+p \to p+\pi^0 +\pi^0 . \tag{3}$$

Reaction (1) has been the first to be studied and is the only one for which there is an extensive amount of experimental data. Some very limited experimental data is available for reaction (2). There is practically no information for channel (3).

The first experimental evidence of existence of the reaction (1) was obtained at Caltech by detecting π^- emitted from a H_2 target bombarded by a bremsstrahlung beam [1,2]. These results were confirmed by the measurements of FRIEDMAN and CROWE [3] at Stanford using a magnetic spectrometer. Afterwards, BLOCH and SANDS [4,5], using a similar experimental technique, but working at higher photon energies made the first detailed study of the reaction. They measured the differential cross-section for an incident-γ-ray energy of 1010 MeV. Their work was the first to indicate that reaction (1) tends to

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(1) V. Z. PETERSON and I. G. HENRY: *Phys. Rev.*, **96**, 850 (1954).
(2) V. Z. PETERSON: *Bull. Am. Phys. Soc.*, Series II, **1**, 173 (1956).
(3) R. M. FRIEDMAN and K. M. CROWE: *Phys. Rev.*, **105**, 1369 (1957).
(4) M. BLOCH and M. SANDS: *Phys. Rev.*, **108**, 1101 (1957).
(5) M. BLOCH and M. SANDS: *Phys. Rev.*, **113**, 305 (1959).

behave in certain cases as nearly a two-body reaction, that is

$$\gamma + p \rightarrow \mathcal{N}^* + \pi .$$

The first measurement of the total cross-section for energies < 950 MeV was made at Cornell [6,7] in a hydrogen filled diffusion cloud chamber. This measurement clearly showed the major characteristic of the double-pion photoproduction; namely that π^+ and π^- play quite different roles. The authors found that an appreciable fraction of the final state was reached through the channel $\pi^-\mathcal{N}^{*++}$ with subsequent decay of the $\mathcal{N}^*$ into $\pi^+ + p$. The total cross-section shows a very peculiar shape with an abrupt rise at threshold, which is very similar to the electric dipole S-wave production of π^+ in H_2 near threshold. The fast rise at 500 MeV is near threshold for the production of a π and an $\mathcal{N}^*$ ($E_\gamma \approx 545$ MeV).

This confirms the statement by BLOCH and SANDS that the reaction should go through the channel $\pi\mathcal{N}^*$. Some later measurements at Frascati [8] seemed to indicate that pion-pairs photoproduction might proceed through the intermediate formation of the $\mathcal{N}^{**}(1512)$ resonance which decays into the $\mathcal{N}^*(1238)$ by emission of a pion.

The $\mathcal{N}^*(1238)$ subsequently decays into a π and a nucleon according to the scheme

$$\gamma + p \rightarrow \mathcal{N}^{**} \rightarrow \pi + \mathcal{N}^* \quad \hookrightarrow \pi + \mathcal{N} .$$

A detailed investigation of reaction (1) was made at Stanford [9] and Tokyo [10], where they measured the angular distributions and calculated the total cross-section for energies lower than 1 GeV. The same reaction has also been studied with hydrogen bubble chambers at CEA [11] and DESY [12].

(6) J. M. SELLEN, G. COCCONI, V. T. COCCONI and E. L. HART: *Phys. Rev.*, **113**, 1323 (1959).

(7) B. M. CHASAN, G. COCCONI, V. T. COCCONI, R. M. SCHECHTMAN and D. H. WHITE: *Phys. Rev.*, **119**, 811 (1960).

(8) M. BENEVENTANO, R. FINZI, L. PAOLUZI, F. SEBASTIANI, M. SEVERI and F. VILLA: *Nuovo Cimento*, **30**, 1054 (1965).

(9) J. V. ALLABY, H. L. LYNCH and D. M. RITSON: *Phys. Rev.*, **142**, 887 (1966).

(10) A. KUSUMEGI, Y. KOBAYASHI, Y. MURATA, H. SASAKI, K. TAKAMATSU and A. MASAIKE: *Proceedings of the International Symposium on Electron and Photon Interactions at High Energies*, vol. **2** (Hamburg, 1965), p. 253.

(11) H. R. CROUCH Jr., R. HARGRAVES, B. KENDALL, R. E. LANOU, A. M. SHAPIRO, M. WIDGOFF, G. E. FISHER, A. E. BRENNER, M. E. LAW, A. E. RONAT, K. STRAUCH, J. C. STREET, J. J. SZYMANSKY, J. D. TEAL, P. BASTIEN, Y. EISENBERG, B. T. FELD, V. K. FISCHER, I. A. PLESS, A. ROGERS, C. ROGERS, L. ROSENSON, T. L. WATTS, R. K. YAMAMOTO, L. GUERRIERO and G. A. SALANDIN: *Phys. Rev. Lett.*, **13**, 636, 640 (1964);

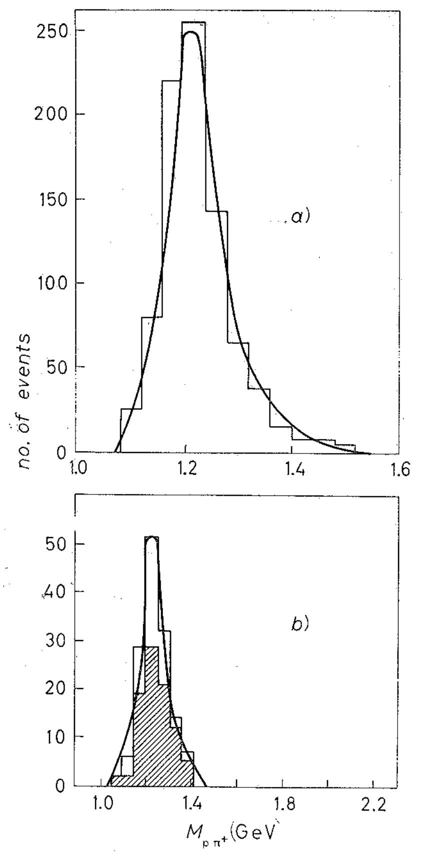

Fig. 1. – Invariant mass of the π^+p system in double-pion photoproduction on hydrogen. The shaded area of the CEA results corresponds to events with momentum transfer $t < 0.2$ $(\text{GeV}/c)^2$. *a*) DESY ([12]), $E_\gamma < 1.1$, *b*) CEA ([11]), $0.65 < E_\gamma < 0.9$.

The essential feature of this reaction as shown by these experiments is its tendency to behave as a two-body reaction, that is

$$\gamma + \text{p} \to \mathcal{N}^* + \pi \, .$$

There are two possible intermediate channels

a) $\pi^- + \mathcal{N}^{*++}$,

b) $\pi^+ + \mathcal{N}^{*0}$.

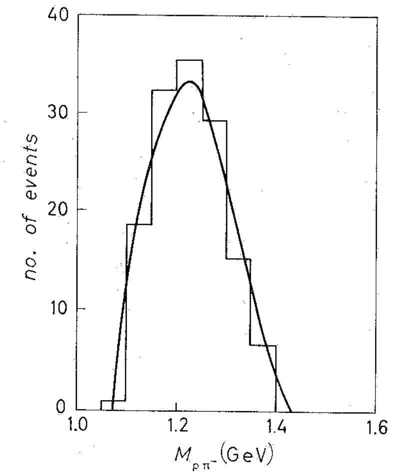

Fig. 2. – Invariant mass of the π^-p system in the CEA experiment. The solid line indicates the distribution obtained only from phase-space production. $0.65 < E_\gamma < 0.9$.

H. R. Crouch jr., R. Hargraves, B. Kendall, R. E. Lanou, A. M. Shapiro, M. Widgoff Shapiro, G. E. Fischer, C. Bordner, A. E. Brenner, M. E. Law, U. Maor, T. A. O'Halloran jr., K. Strauch, J. C. Street, J. J. Szymansky, J. D. Teal, P. Bastien, B. T. Feld, V. K. Fischer, I. A. Pless, A. Rogers, C. Rogers, E. E. Ronat, L. Rosenson, T. L. Watts, R. K. Yamamoto, G. Calvelli, F. Gasparini, L. Guerriero, J. Massimo, G. A. Salandin, L. Ventura, C. Voci, F. Waldner, A. Bandstetter, Y. Eisenberg and A. Levy: *Proceedings of the International Symposium on Electron and Photon Interactions at High Energies*, vol. **2** (Hamburg, 1965), p. 1; Cambridge Bubble-Chamber Group: *Phys. Rev.*, **146**, 994 (1966).

([12]) DESY Bubble-Chamber Group: *Proceedings of the International Symposium on Electron and Photon Interactions at High Energies*, vol. **2** (Hamburg, 1965), p. 36; Aachen-Berlin-Bonn-Hamburg-Heidelberg-München Collaboration: *Nuovo Cimento*, **41** A, 270 (1966).

In Fig. 1 we have shown the plot of the invariant pion nucleon mass for the $p\pi^+$ system. This plot can be interpreted as a combination of phase-space and resonant production.

In Fig. 2 we have shown the same plot for the $p\pi^-$ system. This plot is compatible with phase-space production only.

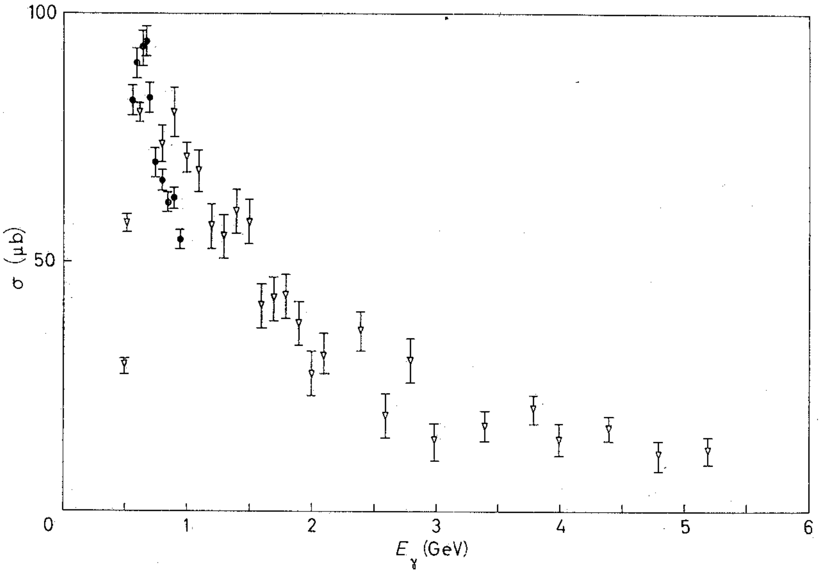

Fig. 3. – Total cross-section for the reaction $\gamma+p\to p+\pi^++\pi^-$. • Stanford (9), ▿ DESY (12).

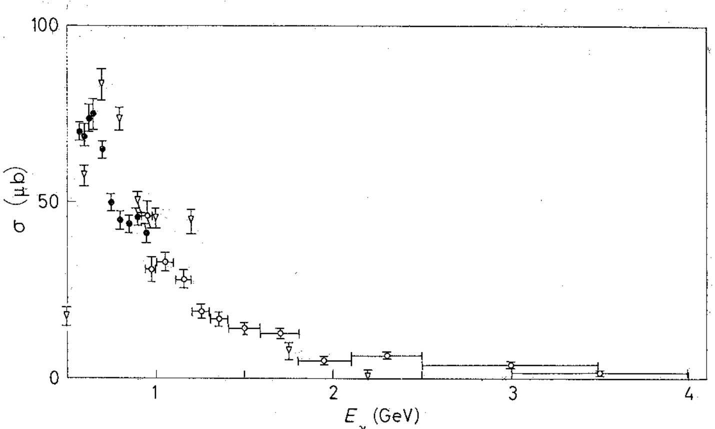

Fig. 4. – Total cross-section for the reaction $\gamma+p\to\mathcal{N}^{*++}+\pi^-$. • Stanford (9), ▿ DESY (12), ○ DESY (53).

Fig. 3 and Fig. 4 show respectively the total cross-section for the reaction $\gamma+p\to\pi^++\pi^-+p$ and for the particular channel $\gamma+p\to\mathcal{N}^{*++}+\pi^-$. The pronounced peak in the cross-section at 600 MeV might well correspond to the p_{11} resonance which has been recently postulated by many authors ([13]) to ex-

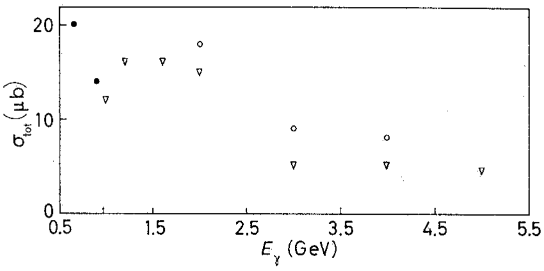

Fig. 5. – Total cross-section for the reaction $\gamma+p\rightarrow p+\pi^++\pi^-$, in the nonresonant channels (phase-space production). • Stanford ([9]), ▿ DESY ([12]), ○ CEA ([11]).

plain the elastic pion-nucleon scattering data. Above this peak there is a rapid drop in the total cross-section. The resonant channel drops very fast and is small and practically constant above 2 GeV. The phase production decreases less rapidly as indicated in Fig. 5.

Figures 6 and 7 show the angular distributions in the c.m. system for the reaction $\pi^-\mathcal{N}^{*++}$ ([9]). The distributions are very flat at threshold and become increasingly forward peaked at higher energies. The strong increase at small angles supports a one-pion-exchange production model (OPE). The angular distributions were fitted by polynomials of the type

$$\frac{d\sigma}{d\Omega^*}(\theta^*) = \sum_{n=0}^{n=1} a_n \cos^n \theta^* \, .$$

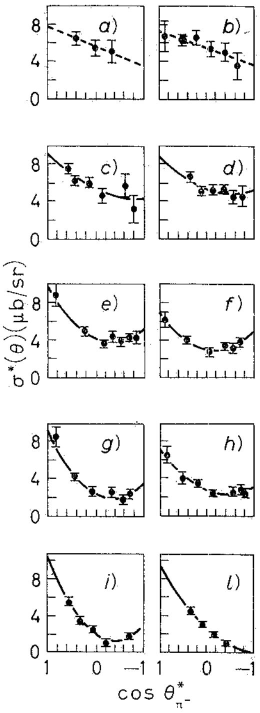

Fig. 6. – Angular distributions in the c.m.s. for π^- in the reaction $\gamma+p\rightarrow\mathcal{N}^{*++}+\pi^-$; Stanford's ([9]) results. *a*) $K_\gamma = 575$ MeV, *b*) $K_\gamma = 600$ MeV, *c*) $K_\gamma = 625$ MeV, *d*) $K_\gamma = 650$ MeV, *e*) $K_\gamma = 700$ MeV, *f*) $K_\gamma = 750$ MeV, *g*) $K_\gamma = 800$ MeV, *h*) $K_\gamma = 850$ MeV, *i*) $K_\gamma = 900$ MeV, *l*) $K_\gamma = 950$ MeV.

For energies < 1 GeV powers not higher than $\cos^2\theta^*$ are involved. Figure 8 shows the coefficients a_0, a_1, a_2 *vs.* incident γ-energy.

([13]) G. Cocconi, E. Lillethun, J. P. Scanlon, C. A. Stahlbrandt, C. C. Ting, J. Walters and A. M. Wetherell: *Phys. Lett.*, **8**, 134 (1964); P. Bareyre, C. Bricman, G. Valladas, G. Villet, J. Bizard and J. Seguinot: *Phys. Lett.*, **8**, 137 (1964); L. D. Roper: UCRL 7846 and *Phys. Rev. Lett.*, **12**, 340 (1964); S. L. Adelman: *Phys. Rev. Lett.*, **13**, 555 (1964); P. Auvil and C. Lovelace: *Nuovo Cimento*, **33**, 473 (1964).

This trend is confirmed at higher energies as indicated by the measurements of CEA [11] and HAUSER and WALKER [14].

The influence of any pion-pion interaction seems to be small, but so far the theory and the experiment are not accurate enough for any clear statement.

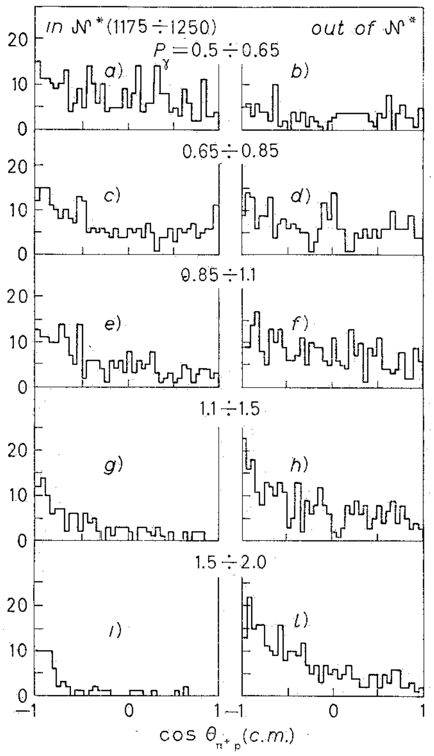

Fig. 7. – Angular distributions of the πp system in the c.m.s. for the reaction $\gamma+p \to \mathcal{N}^{*++}+\pi^-$; Results of the Cambridge Bubble Chamber Group (CEA) [11].

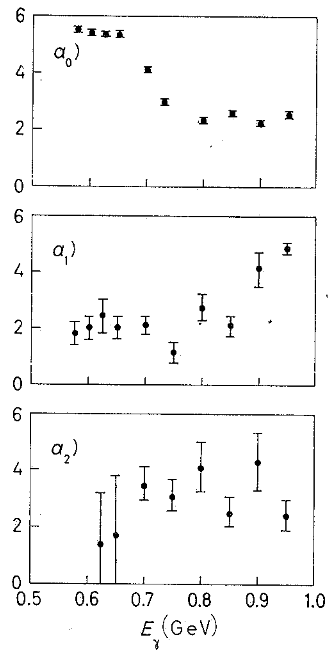

Fig. 8. – The coefficients of the differential cross-section $d\sigma/d\Omega^* = \sum_{n=0}^{n=2} a_n \cos^n(\theta^*)$, for the reaction $\gamma+p \to \mathcal{N}^{*++}+\pi^-$; Stanford [9] results.

Measurements at higher energies have been performed at CEA [11] in the energy range (0.5÷4.0) GeV and have been extended at DESY [12] up to 5.5 GeV. These experiments indicate that reaction (1) behaves in most cases like a quasi-two-body reaction. Unlike the energy region below 1 GeV where the reaction is dominated by the formation of the first pion-nucleon isobar,

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[14] M. G. HAUSER and R. L. WALKER: *Photoproduction of Negative Pions from Hydrogen*, CALT-68-71 (1966).

the high-energy region is dominated by the formation of a rho. This is strictly analogous to what happens in similar processes initiated by pions [15].

The results of DESY concerning the probability of formation of the various resonances are summarized in Table II as a function of the γ-ray energy.

TABLE II.

E_γ	$\mathcal{N}^*$(%)	ρ^0(%)	Phase space (%)
1.1	84	0	16
1.1÷1.4	41	30	29
1.4÷1.8	13	50	37
1.8÷2.4	3	48	49
2.5÷3.5	11	56	33
3.5÷5.5	0	65	35

The first theoretical model for double-pion photoproduction was introduced by CUTKOSKY and ZACHARIASEN [16]. They extended the static model used by CHEW and LOW [17,18] for single-pion photoproduction to the photoproduction of two pions at low energy. This model assumes the emission of a P-wave pion and an S-wave pion. The emission of both pions in an S-state is ignored due to the absence of any possible pion-nucleon resonant state. The emission of two P-wave pions is also neglected because there is not enough energy to overcome the centrifugal barrier. The model takes into account only contributions from diagrams where there is only one pion exchanged. The results of this model are not in agreement with experiments. Figure 9 indicates the

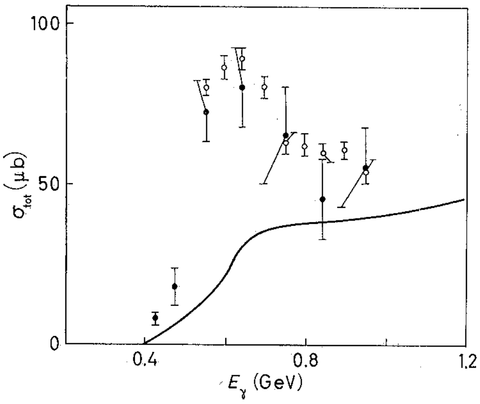

Fig. 9. – Comparison of the theoretical prediction of the model of CUTKOSKY and ZACHARIASEN for the total cross-section for the reaction $\gamma+p\to p+\pi^++\pi^-$ with the experimental data. ○ Stanford [9], ● CHASAN, *et al.* [7], ——— CUTKOSKY and ZACHARIASEN [16].

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[15] J. KIRZ, J. SCHWARZ and R. D. TRIPP: *Phys. Rev.*, **130**, 2481 (1963); V. P. KENNEY, J. L. STAUTBERG and C. N. VITTITOE: *Bull. Am. Phys. Soc.*, Series, II, **8**, 523 (1963); J. P. MERLO and G. VALLADAS: *The reaction* $\pi+\mathcal{N}\to\mathcal{N}^*(1238)$ *near the* $\mathcal{N}^*(1510)$ *and the* $\mathcal{N}^*(1690)$ *resonances*, C.E.A. Saclay.

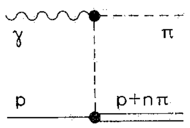
[16] R. E. CUTKOSKY and F. ZACHARIASEN: *Phys. Rev.*, **103**, 1108 (1956).

[17] F. E. LOW: *Phys. Rev.*, **97**, 1392 (1955).

[18] G. F. CHEW and F. E. LOW: *Phys. Rev.*, **101**, 1579 (1956).

results for the total cross-section compared with the experimental data. The most striking difference appears close to the threshold. The same poor agreement is found in the angular distributions. The model predicts an isotropic distribution for the π^- while the experimental data shows strong evidence of a forward peak (Fig. 6 and 7).

The forward peaking of the angular distributions at high energy suggests a peripheral model of production. DRELL [19] suggested a one-pion exchange model (OPE). He calculated the graph:



which is believed to be the most important at small angles and energies above 1 GeV. The exchanged pion is assumed to be on the mass shell and the lower vertex is calculated from the total cross-section for pion-nucleon scattering.

The model is not in quantiative agreement with the experiment. The experimental values of the total cross-sections are higher than calculated as is indicated in Table III. Moreover the model predicts a distribution of the type $1+3\cos^2\theta$ for the proton in the $\mathcal{N}^*$ rest system. The experimental distributions appear isotropic (Fig. 10).

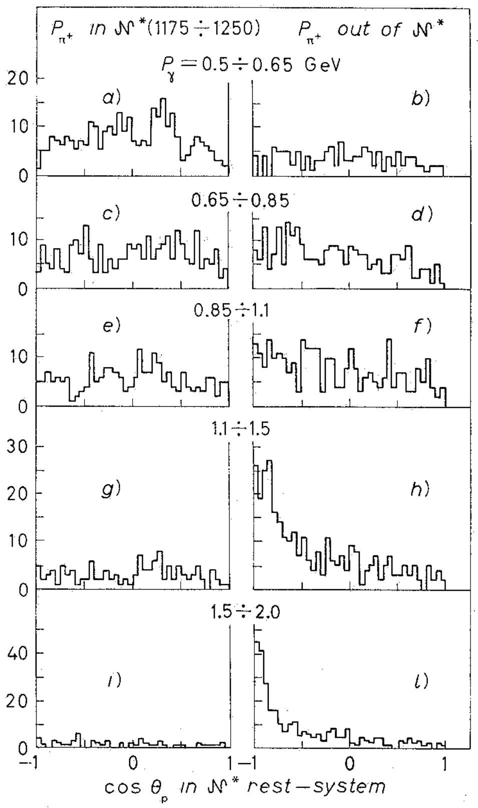


Fig. 10. – $\mathcal{N}^*$ decay angular distribution in the $\mathcal{N}^*$ rest system. θ is the angle between the direction of the decay proton and the direction of motion of the $\mathcal{N}^*$. Results of CEA [11]. *a*) 296 events, *b*) 133 events, *c*) 274 events, *d*) 265 events, *e*) 223 events, *f*) 307 events, *g*) 124 events, *h*) 314 events, *i*) 58 events, *l*) 287 events.

ITABASHI [20] and HADJIOANNOU [21] have introduced some improvements in the static theory of CUTKOSKY and ZACHARIASEN. They took into account

[19] S. D. DRELL: *Phys. Rev. Lett.*, **5**, 278, 342 (1960); *Rev. Mod. Phys.*, **33**, 458 (1961).

[20] K. ITABASHI: *Phys. Rev.*, **123**, 2157 (1961).

[21] F. HADJIOANNOU: CERN, Report 1962.

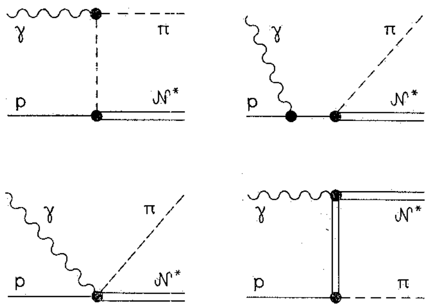
the nucleon's recoil and modified the $\mathcal{N}\pi$ system introducing a cut-off function of the type suggested by FUBINI and THIRRING (22).

Their results show a satisfactory agreement with the experimental data in the region around 1.3 GeV.

TABLE III.

E_γ (GeV)	exp. (μb)	σ OPE (μb)
0.7 ÷ 0.9	27 ± 11	7.2
0.9 ÷ 1.1	21 ± 8	6.4
1.1 ÷ 1.8	10 ± 5	4.2
1.8 ÷ 6.0	≲ 1	3.0

More recently STICHEL and SCHOLZ (23) made a gauge-invariant generalization of the OPE model taking into account the following graphs:



Both the total cross-section and the angular distributions calculated by them are in good agreement with the experimental data of DESY (12) as is indicated in Fig. 11. It is interesting to note that at the limit for infinite nucleon mass this calculation agrees with the results of Itabashi, and Hadjioannou.

At present we have very limited information about the reactions $\gamma+p\to n+\pi^++\pi^0$. BLOCH and SANDS (4,5) found that the yield of positive pions from double-pion photoproduction is twice the same yield for negative pions. This indicates that the cross-section for the reactions

$$\gamma+p\to p+\pi^++\pi^-$$

and

$$\gamma+p\to n+\pi^++\pi^0$$

(22) S. FUBINI and W. E. THIRRING: *Phys. Rev.*, **105**, 1382 (1957).
(23) P. STICHEL and M. SCHOLZ: *Nuovo Cimento*, **34**, 1381 (1964).

are comparable. The same result has been obtained by FRIEDMAN and CROWE [2] and by KUSUMEGI *et al.* [10].

A similar conclusion has been reached recently measuring the total neutron yield from a hydrogen target bombarded by high-energy γ-rays [24]. This

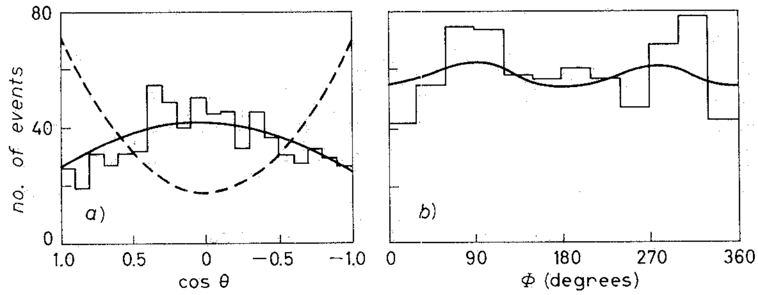


Fig. 11. – $\mathcal{N}^*$ decay angular distribution in the $\mathcal{N}^*$ rest system. In *a*) θ is the angle between the direction of the decay proton and the direction of motion of the $\mathcal{N}^*$. In *b*) Φ is the azimuthal angle with respect to the production plane. DESY [12] results for $E_\gamma < 1.1$ GeV, $\Delta^2(p/p\pi^+) < 0.5$ GeV^2 and 1.12 GeV$< M_{p\pi^+} < 1.32$ GeV. The broken line gives the prediction of the OPEM $(1+3\cos^2\theta)$ and the solid line gives the result of the OPE model with the corrections of STICHEL and SCHOLZ [23]. $\gamma p \to \mathcal{N}^{*++}\pi^-$. 717 events.

fact contradicts the theoretical calculations of CUTKOSKY and ZACHARIASEN which predicted a ratio of 5:1.

No useful experimental results are available for the reaction $\gamma + p \to \to p + \pi^0 + \pi^0$. The experiments of VETTE *et al.* [25] and those of BINGHAM and CLEGG [26], who measured the photoproduction of single neutral pions in hydrogen, indicate that the cross-section for this process is very small.

3. – Boson photoproduction.

At energies above 1 GeV, the photoproduction of ρ and ω mesons becomes kinematically possible. The first evidence of ρ photoproduction on protons came from the experiment of MC LEOD and co workers [27] in 1961. Later, the

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[24] S. COSTA, S. FERRONI, V. G. GRACCO, C. SCHAERF and E. SILVA: *Nuovo Cimento*, **45** A, 696 (1966).

[25] J. I. VETTE: *Phys. Rev.*, **111**, 622 (1958).

[26] H. H. BINGHAM and A. B. CLEGG: *Phys. Rev.*, **112**, 2053 (1958).

[27] D. M. MCLEOD, S. RICHERT and A. SILVERMAN: *Phys. Rev. Lett.*, **7**, 383 (1961).

photoproduction of the η meson was measured at Frascati [28] and Orsay [29]. The photoproduction of the omega was put in evidence more recently in a bubble chamber experiment performed at CEA [11] and DESY [12]. Many experiments were also dedicated to the search for other boson resonances of lower mass. No conclusive evidence of such resonances has been found up to now.

a) *η-meson.* According to SU_3 the η^0 belongs to the same 0^- octet as the π and K mesons. Since there is available a large amount of experimental information on the photoproduction of π and K mesons, photoproduction of η^0 can be used to test specific theoretical predictions. This is of special interest at energies far above threshold. In particular, some interesting observations have been made by a direct comparison of the reactions:

$$(4) \qquad \begin{cases} a)\ \gamma+\mathrm{p} \to \pi^0+\mathrm{p}\,, & c)\ \gamma+\mathrm{p} \to \eta^0+\mathrm{p}\,, \\ b)\ \pi^-+\mathrm{p} \to \pi^0+\mathrm{n}\,, & d)\ \pi^-+\mathrm{p} \to \eta^0+\mathrm{n}\,. \end{cases}$$

We have available at present, only a limited amount of experimental information on the photoproduction of the η particle. The first experiments were performed at Frascati [28], detecting the recoil proton in coincidence with one of the γ's from the decay of the η, and at Orsay [29] by the excitation curve method detecting the recoil proton. Both experiments have suggested a large cross-section close to threshold. This indication has been confirmed by the more recent results of Stanford [30], Frascati [31] and Orsay [29bis].

The differential cross-section measured around a center-of-mass angle of 110° [28-31] shows a rise at threshold followed by a rapid decrease around a γ-ray energy of 900 MeV as is clearly indicated in Fig. 12. This same trend

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(28) C. MENCUCCINI, R. QUERZOLI, G. SALVINI and V. SILVESTRINI: *Proceedings of the International Conference on High-Energy Nuclear Physics* (Geneva, 1962); C. BACCI, G. PENSO, G. SALVINI, A. WATTENBERG, C. MENCUCCINI, R. QUERZOLI and V. SILVESTRINI: *Phys. Rev. Lett.*, **11**, 37 (1963).

(29) B. DELCOURT, J. LEFRANÇOIS and J. P. PEREZ Y JORBA: *Phys. Lett.*, **7**, 215 (1963).

(29bis) B. DELCOURT, J. LEFRANÇOIS, J. P. PEREZ Y JORBA and J. SAUVAGE: private communication and presented to the *XIII International Conference on High-Energy Physics, Berkeley*, 1966.

(30) R. PREPOST, D. LUNDQUIST and D. QUINN: *Proceedings of the International Symposium on Electron and Photon Interactions at High Energies*, vol. **2** (Hamburg, 1965), p. 152.

(31) C. BACCI, G. PENSO, G. SALVINI, C. MENCUCCINI and V. SILVESTRINI: *Proceedings of the International Symposium on Electron and Photon Interactions at High-Energies*, vol. **2** (Hamburg, 1965), p. 158; *Phys. Rev. Lett.*, **16**, 157 (1966).

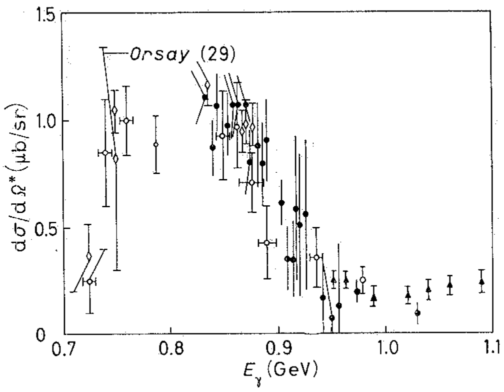


Fig. 12. – Differential cross-section for the reaction $\gamma+p\to p+\eta^0$ as a function of the gamma-ray energy at various angles in the center-of-mass system. ○ Stanford (~90°) ([30]), • Frascati (106°÷118°) ([31]), ▲ Caltech (45°) ([33]), ◇ Orsay (98°÷160°) ([29bis]).

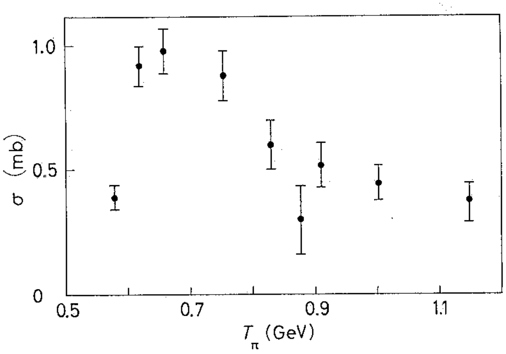


Fig. 13. – Total cross-section for the reaction $\pi^-+p\to n+\eta^0$ as a function of the kinetic energy of the incoming pion in the laboratory system. Only events corresponding to the particular decay channel $\eta^0\to 2\gamma$ have been detected.

has been found ([32]) for the total cross-section for reaction 4*d*) (see Fig. 13). It should be noted that in this experiment, as in the Frascati experiments, only the particular decay channel $\eta^0\to 2\gamma$, has been detected. This fact can account for a possible discrepancy among the absolute values of the cross-section. More recent data from Caltech ([33]) of the differential cross-sections for reaction 4*c*) at a center-of-mass angle of 45° extends the previous measurements to higher energies. This result is also indicated in Fig. 12. The only significant measurement of an angular distribution has been made at Stanford ([30]) for a γ-ray energy of 790 MeV. These results (see Fig. 14) are consistent with an *S*-wave production model.

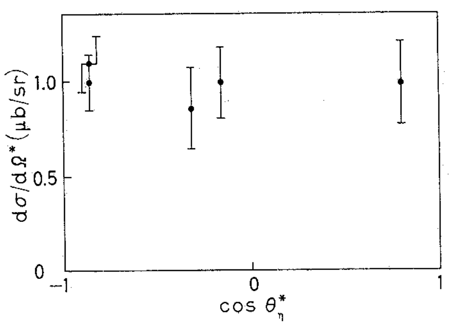


Fig. 14. – Angular distribution for the reaction $\gamma+p\to p+\eta^0$ at a gamma-ray energy of 0.790 GeV. The results are from ref. ([30]).

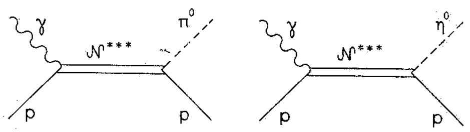
From a theoretical point of view we

([32]) F. Bulos, R. E. Lanou, A. E. Pifer, A. M. Shapiro, M. Widgoff, R. Pavini, A. E. Brenner, C. A. Bordner, M. E. Law, E. E. Ronat, K. Strauch, J. J. Szymansky, P. Bastien, B. B. Brabson, Y. Eisenberg, B. T. Feld, V. K. Fisher, I. A. Pless, L. Rosenson, R. K. Yamamoto, G. Calvelli, L. Guerriero, G. A. Salandin, A. Tomasin, L. Ventura, C. Voci and F. Waldner: *Phys. Rev. Lett.*, **13**, 486 (1964).

([33]) C. A. Heusch, C. Y. Prescott, E. D. Bloom and L. S. Rochester: *Phys. Rev. Lett.*, **17**, 573 (1966).

can note that both the second $\mathcal{N}^{**}(1512)$ and third $\mathcal{N}^{***}$ (1688) pion-nucleon resonance could decay into a nucleon and η-meson. However, the second resonance is only 20 MeV above threshold. Since, near threshold, the D-wave production goes like q^4 (q indicates the momentum in the c.m.s.), it is reasonable to assume that its contribution is irrelevant.

The third pion-nucleon resonance can, in principle, decay into a nucleon and an η meson. Therefore, we will focus our attention on the two possible graphs:



the left-hand vertices are the same in both graphs, while the ratio of the right-hand vertices are predictable on the basis of SU_3. This ratio depends strongly on the SU_3 assignment of the $\mathcal{N}^{***}$. We can write

$$\frac{(\gamma p \to \mathcal{N}^{***} \to p\eta)}{(\gamma p \to \mathcal{N}^{***} \to p\pi^0)} = \frac{\varrho(\eta) R}{\varrho(\pi^0)},$$

where $\varrho(\eta)$ and $\varrho(\pi^0)$ are kinematical factors and R can be expressed in terms of the reduced widths (γ) of the various vertices, *i.e.*

$$R = \frac{\gamma_{\mathcal{N}^{***}\mathcal{N}\eta}}{\gamma_{\mathcal{N}^{***}\mathcal{N}\pi^0}} = \begin{cases} 3 \\ \frac{1}{3}(3-4\alpha)^2 \end{cases} \text{if } \mathcal{N}^{***} \begin{cases} \in 27 \\ \in 8 \end{cases} \text{in } SU_3 .$$

$\alpha/(1-\alpha)$ is the ratio of D- to F-type couplings for which we can tentatively assume $\alpha = \frac{2}{3}$ (34). In this way we obtain

$$\frac{\sigma(\eta)}{\sigma(\pi)} \simeq \begin{cases} 1 \\ \text{very small} \end{cases} \text{if } \mathcal{N}^{***} \begin{cases} \in 27 , \\ \in 8 . \end{cases}$$

As is clear from Fig. 12 there is no evidence for a resonant behaviour of the differential η photoproduction cross-section at energies comparable with the third isobar. This should encourage the assignment of the $\mathcal{N}^{***}(1688)$ to a new SU_3 octet with quantum numbers $J^P = \frac{5}{2}^+$.

At CALTECH, HEUSCH *et al.* (34bis), starting from a more stringent analysis of the experimental data arrived to the same conclusion and were able to

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(34) R. F. DASHEN: *Nuovo Cimento*, **32**, 469 (1964).
(34bis) C. A. HEUSCH, C. Y. PRESCOTT and R. F. DASHEN: *Phys. Rev. Lett.*, **17**, 1019 (1966).

set some limits on the possible values of α:

$$0.5 \leqslant \alpha_{\exp} \leqslant 1.0 \,.$$

The agreement of this limit with the previous theoretical estimate is very remarkable.

A direct comparison of reactions (4) has been made by the Frascati group [31]. Considering that reactions (4*c*) and (4*d*) are in a pure $T = \frac{1}{2}$ state we have to isolate the particular $T = \frac{1}{2}$ channel in pion-nucleon scattering and pion photoproduction. For pion scattering we can immediately write

$$\sigma_\pi^{\frac{1}{2}} = \tfrac{3}{2}[\sigma(\pi^-, \pi^-) + \sigma(\pi^-, \pi^0) - \tfrac{1}{3}\sigma(\pi^+, \pi^+)] \,,$$

where $\sigma(\pi^-, \pi^-)$, $\sigma(\pi^+, \pi^+)$ and $\sigma(\pi^-, \pi^0)$ are respectively the cross-sections for the reactions $\pi^- + p \rightarrow \pi^- + p$, $\pi^+ + p \rightarrow \pi^+ + p$ and reaction (4*b*). This separation in isospin states is valid both for the differential cross-sections at a particular angle and for the total cross-section. The situation is more complicated for the photoproduction cross-section. In fact, in this case it is not possible to separate the various isospin amplitudes on the basis of any measurable set of data. However, we can observe that if the $T = \frac{3}{2}$ amplitude is negligible, then we should have

$$\sigma(\gamma, \pi^+) = 2\sigma(\gamma, \pi^0) \,,$$

where $\sigma(\gamma, \pi^+)$ and $\sigma(\gamma, \pi^0)$ represent respectively the cross-sections for reactions $\gamma + p \rightarrow \pi^+ + n$ and $\gamma + p \rightarrow \pi^0 + p$.

This ratio is approximately true at a pion angle of 180° where the direct photoproduction term is zero. If we now assume that in this energy region the direct photoproduction term is the only term responsible for transitions in the $T = \frac{3}{2}$ state, we can write (*)

$$\sigma_\gamma^{\frac{1}{2}} = 3\sigma(\gamma, \pi^0) \,.$$

Let us now define

$$R_\gamma(\theta) = \frac{\mathrm{d}\sigma^{\frac{1}{2}}/\mathrm{d}\Omega^*}{\mathrm{d}\sigma^{\eta 0}/\mathrm{d}\Omega^*} \,, \qquad R_\pi(\theta) = \frac{\mathrm{d}\sigma_\pi^{\frac{1}{2}}/\mathrm{d}\Omega}{\mathrm{d}\sigma^{\eta 0}/\mathrm{d}\Omega}$$

(*) The matrix element for pion photoproduction can be written is isospin space as the sum of the terms $H = S + V_3$, where S transforms like a scalar and V_3 like the third component of an isovector. If we consider only $T = \frac{1}{2}$ final states we have [35] $\langle \frac{1}{2}, m|V_3|\frac{1}{2}, m'\rangle = \delta_{mm'} t_1 m$, $\langle j, m|S|^{j'}, m'\rangle = \delta_{mm'}\delta_{jj'} S_0$, and using the Clebsch-Gordan coefficients $\langle \pi^0 p| = -\sqrt{\frac{1}{3}}\langle \frac{1}{2}, \frac{1}{2}| + \sqrt{\frac{2}{3}}\langle \frac{3}{2}, \frac{1}{2}|$, $\langle \eta^0 p| = \langle \frac{1}{2}, \frac{1}{2}|$, from this we can write $\langle \pi^0 p|H|\frac{1}{2}, \frac{1}{2}\rangle = -\sqrt{\frac{1}{3}}(\frac{1}{2}t_1 + S_0)$, $\langle \eta^0 p|H|\frac{1}{2}, \frac{1}{2}\rangle = (\frac{1}{2}t_1 + S_0)$.

[35] K. M. WATSON: *Phys. Rev.*, **85**, 852 (1951).

and a similar quantity R_γ (total) for the total cross-sections. The experimental values of these quantities are reported in Fig. 15. It is interesting to note that the values of R are reasonably constant at γ-ray energies below 900 MeV. The values start to increase at energies where the third isobar becomes significant. This is another indication of the hypothesis that the third resonance tends to favor π over η production.

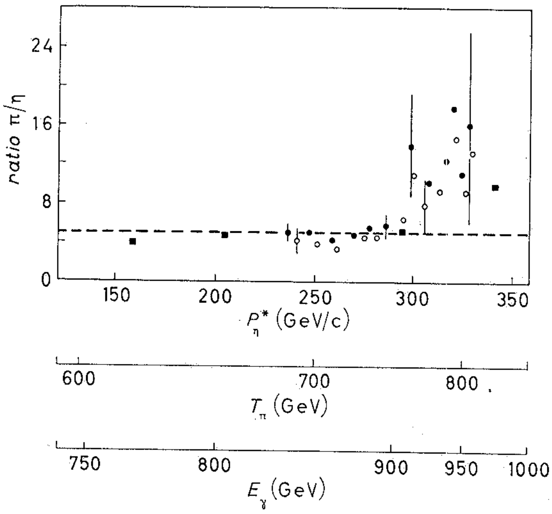
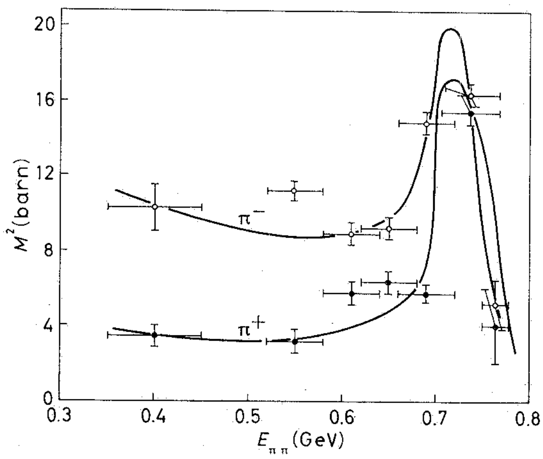


Fig. 15. – Comparison between π and η^0 in photoproduction and scattering experiments. • $R_\gamma(\theta)$ $\theta = 120°$ (Frascati: R. DIEBOLD: *Thesis*), ○ R_γ (total) (Frascati: R. DIEBOLD: *Thesis*), ▪ $R_\pi(\theta)$ $80° < \theta < 120°$ (HALLAND, BULOS, *et al.*).

b) ρ-*meson*. The first evidence of ρ photoproduction on protons was found at Cornell [27] in a magnet and counters experiment detecting in coincidence the recoil proton and one of the pions. The kinematical conditions of this experiment were such as to minimize the effect of the final-state interaction of the nucleon with one of the pions. The square of the matrix element for the reaction $\gamma+p \to p^+ + \pi^+ + \pi^-$ is shown in Fig. 16 as a function of the invariant π-π mass. The clear resonant behaviour at an energy of 720 MeV is compatible with the assumption of the formation of a ρ-meson. Later results

Fig. 16. – The square of the matrix element for the reaction $\gamma+p \to p+\pi^+ + \pi^-$ as a function of the invariant π-π mass.

Curve label	$W_{p\pi^+}$ (GeV)	$W_{p\pi^-}$ (GeV)
π^-	1.161	1.414
π^+	1.414	1.161



at Cornell ([36]) confirmed the previous ones and measured the ρ differential photoproduction cross-section at γ-ray energies between 900 and 1275 MeV. This experiment indicated a resonance at a mass of (740±10) MeV. The differential cross-section (see Table IV and Fig. 17) seems to have a maximum around $\theta_\rho^{\text{c.m.}} = 60°$.

The largest amount of information presently available comes from bubble chamber experiments both at CEA ([11]) and DESY ([12]) and from the Harvard experiment ([37]). The best values for the mass of the ρ and its width that can be obtained by all these experiments, are

$$M_\rho = (745 \pm 10)\ \text{MeV}\,,$$

$$\Gamma_\rho = (145 \pm 10)\ \text{MeV}\,.$$

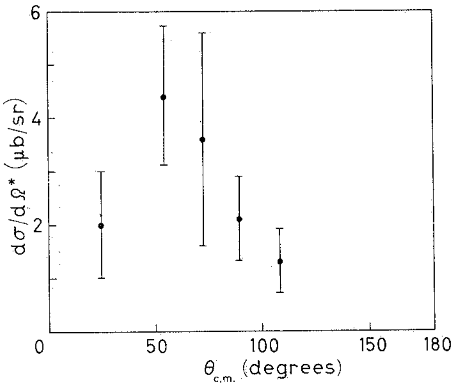


Fig. 17. – Angular distribution for the reaction $\gamma + p \to p + \rho^0$ at a gamma-ray energy of 1.1 GeV.

The percentage of ρ production with respect to the total double-pion production has been indicated in Table II as a function of the incident-γ-ray energy.

TABLE IV.

$\theta^{\text{c.m.}}$	$d\sigma/d\Omega^*$
ρ	μb/sr
0 ÷ 50	2.0 ± 1.0
45 ÷ 63	4.4 ± 1.3
63 ÷ 81	3.6 ± 2.1
81 ÷ 99	2.1 ± 0.8
99 ÷ 117	1.3 ± 0.6

The total cross-section for ρ photoproduction is indicated in Fig. 18 together with the total photoproduction cross-section for pion pairs. The

([36]) A. D. FRANKLIN, D. R. RUST, A. SILVERMAN, C. K. SINCLAIR and R. M. TALMAN: *Phys. Rev. Lett.*, **13**, 491 (1964).

([37]) L. J. LANZEROTTI, R. B. BLUMENTHAL, D. C. EHN, W. L. FAISSLER, P. M. JOSEPH, F. M. PIPKIN, J. K. RANDOLPH, J. J. RUSSEL, D. G. STAIRS and J. TENENBAUM: *Phys. Rev. Lett.*, **15**, 210 (1965); *Proceedings of the International Symposium on Electron and Photon Interactions at High Energies*, vol. **2** (Hamburg, 1965), p. 167.

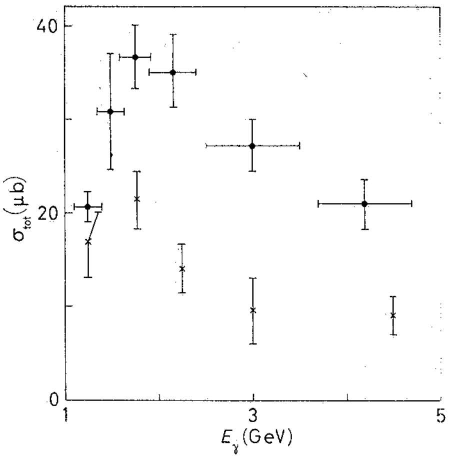


Fig. 18. – Total photoproduction cross-section for ρ meson (× DESY ([12]) $\gamma+p\to p+\rho^0$, ○ CEA ([11]) $\gamma+p\to p+\rho^0$).

cross-section for ρ photoproduction rises sharply at threshold and falls off rather slowly at a value of 15 μb.

The differential cross-section is shown in Fig. 19 for different values of the primary-γ-ray energy. The sharp forward peaking immediately suggests a peripheral production mechanism. In Fig. 20 the differential cross-section as a function of the four-momentum transfer is compared with different peripheral models.

Similar results from Harvard are indicated in Fig. 21 and compared with the t distribution observed in π-p scattering.

ρ photoproduction at 0° has been measured at CEA ([37]) and is reported in Fig. 22. The same measurement has been made at Harvard ([37]) in various elements as a function of the atomic number. (See Fig. 23.)

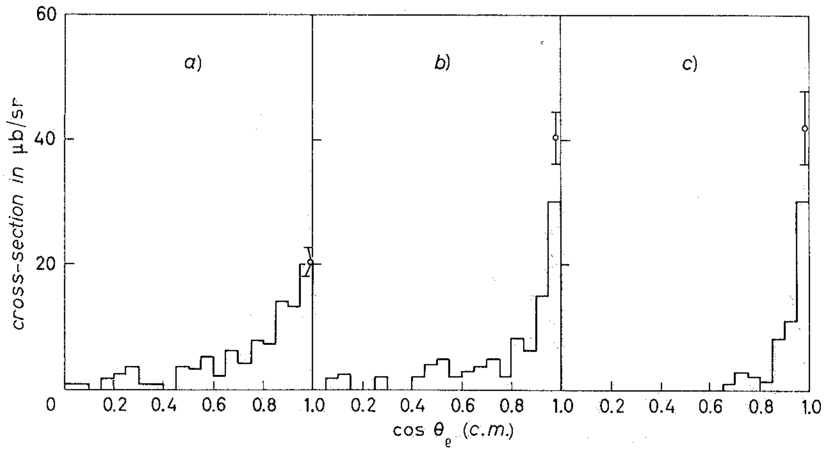


Fig. 19. – Angular distributions of the ρ in the center-of-mass system for the reaction $\gamma+p\to p+\rho^0$. *a*) $1.5<p_\gamma<1.8$ GeV/c, *b*) $1.8<p_\gamma<2.5$ GeV/c, *c*) $2.5<p_\gamma<6.0$ GeV/c.

The polarization of the ρ has been measured at CEA ([11]) measuring the decay pion asymmetry in the rest system of the ρ.

As we mentioned earlier the strong forward peaking in the ρ angular distribution suggests a peripheral production model. The simplest peripheral model is the one-pion exchange model (OPEM). However, in our case this

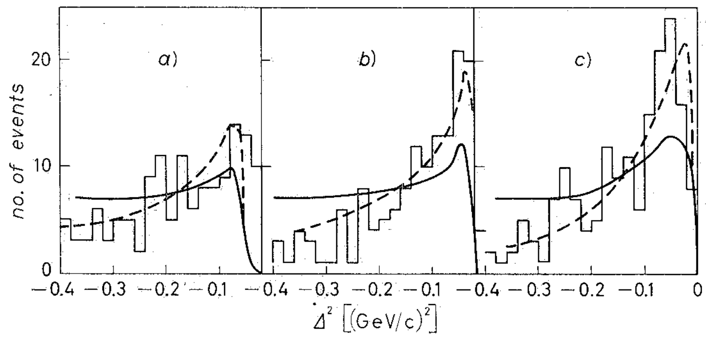


Fig. 20. – Differential cross-section for the reaction $\gamma+p \to p+\rho^0$ as a function of the four-momentum transfer: CEA results. The solid lines indicate the prediction of the OPEM with no absorption in the final state. The broken lines indicate the same results with maximum absorption. *a*) $1.5 < p_\gamma < 1.8$ GeV/c, *b*) $1.8 < p_\gamma < 2.5$ GeV/c. *c*) $2.5 < p_\gamma < 6.0$ GeV/c.

model predicts a dependence as a function of the four-momentum transfer which decreases less rapidly than is indicated by the experimental data (see Fig. 20). Various corrections have been introduced in the OPEM to increase the forward peaking in the angular distribution. FERRARI and SELLERI ([38,39]) have introduced an *ad hoc* form factor as a solution to this problem. More recently, various people ([40]) have calculated the OPEM introducing large absorptive corrections for the wave functions in the initial and final state. This technique has been used for a long time in low-energy nuclear physics. A schematic representation of the distorted-wave Born approximation in high-energy photoproduction can be indicated with the following graph:

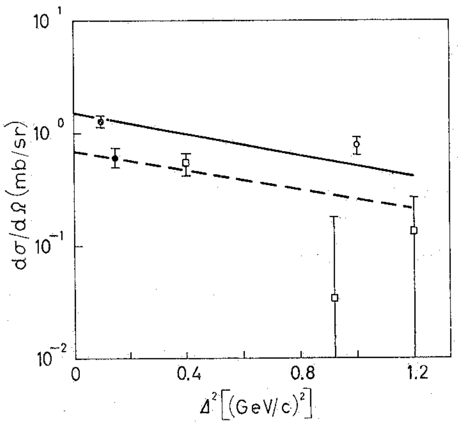
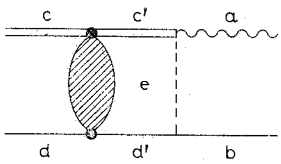


Fig. 21. – Differential cross-section for the reaction $\gamma+p \to p+\rho^0$ as a function of the four-momentum transfer. Harvard results ([37]). The lines indicate the t distribution observed in pion-proton scattering. • 4.40 GeV RHOS, ○ 480 GeV RHOS, □ 2.52 GeV RHOS.



([38]) F. SELLERI: *Phys. Lett.*, **3**, 76 (1962).

([39]) E. FERRARI and F. SELLERI: *Nuovo Cimento*, **27**, 1450 (1963).

([40]) J. D. JACKSON: *Rev. Mod. Phys.*, **37**, 484 (1965); G. KRAMER and K. SHILLING: *Proceedings of the International Symposium on Electron and Photon Interactions at High Energies*, vol. **2** (Hamburg, 1965), p. 316.

The one-particle exchange diagram at the right represents the interaction potential of low-energy nuclear physics. The shaded blob on the left indicates the scattering in the final state. In the limit of very-high-energy particles we can

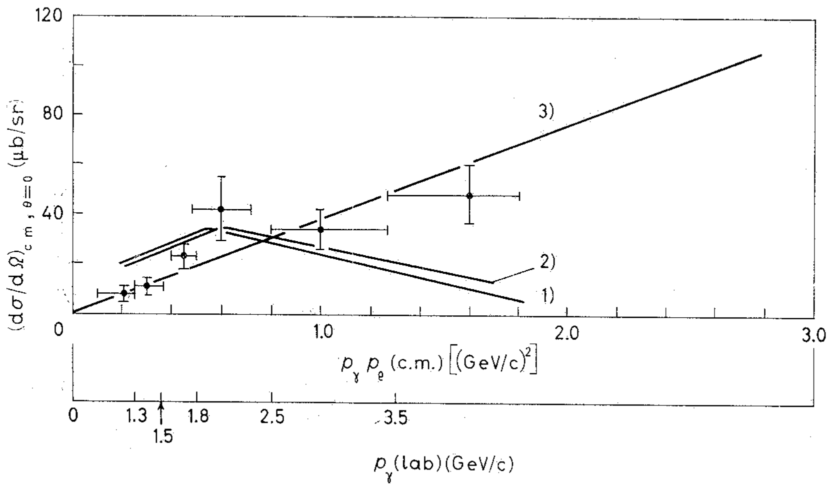


Fig. 22. – Differential ρ-photoproduction cross-section at 0°. The solid lines indicate the theoretical predictions of various models: 1) OPEM no absorption ($c = 0$), 2) OPEM complete absorption ($c = 1$), 3) diffraction model.

assume that the intermediate particles c′ and d′ are on the mass shell and therefore, the scattering in the final state can be expressed in terms of scattering phase shifts.

As is clearly indicated in Fig. 20, the OPEM with absorption gives a better agreement with the experimental data than the simple OPEM. On the other hand, the data of

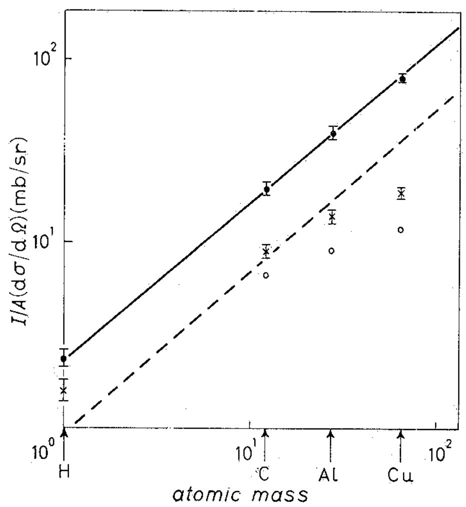
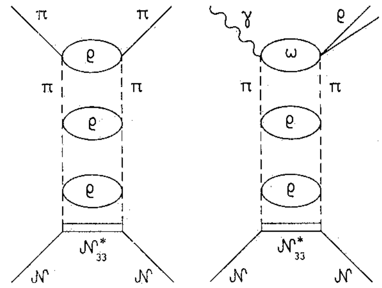


Fig. 23. – Comparison of the differential ρ-photoproduction cross-section at 0° with the cross-section for pion-nuclei scattering at the same angle for various nuclei. The π-scattering curve (solid line) has been shifted (broken line) to the ρ-photoproduction points for comparison. • $\pi+A\to\pi+A$ from optical theorem (×1/100), × $\gamma+A\to\rho+A$ (corrected to $q^2=0$), ∘ $\gamma+A\to\rho+A$ (0°).

DESY (Fig. 24) indicate an even sharper dependence than can be expected with any OPEM. These data seem in agreement with the the diffraction model of BERMAN and DRELL ([41]). They used the multiperipheral scattering model of AMATI, FUBINI and STANGHELLINI ([42]) to correlate this cross-section to the differential cross-section for pion-nucleon scattering. This was achieved replacing the top rungs in the multiperipheral ladder of the AFS model as indicated below.



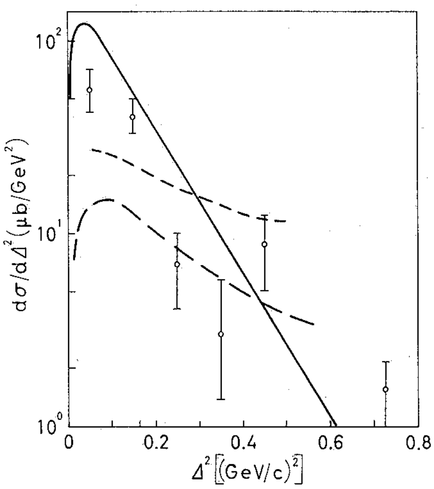


Fig. 24. – Differential ρ-photoproduction cross-section as a function of the four momentum transfer. DESY results ([12]). The data are compared with the theoretical results of various peripheral models; – – – OPEM with absorption, — — — OPEM with Ferrari and Selleri form factor, ——— diffraction model. $\gamma + p \rightarrow \rho^0 + p$. $1.1 < \varepsilon_\gamma < 5.5$ GeV.

The differential cross-section at 0° provides a more sensitive test of the various models proposed. In fact, OPEM would give a cross-section decreasing with energy as $1/E^2$. OPEM with absorption would also give a decreasing trend, but a less pronounced one. On the other hand, the diffraction model gives a cross-section increasing with energy in much better agreement with the experimental data as is indicated in Fig. 22.

The angular distribution of the pions from the ρ decay provides independent information to compare with the different theoretical models. We can consider three different angular distributions:

1) The Treiman-Yang angle. The angle between the production plane (the plane defined by the incident γ-ray and the recoil proton) and the decay plane (the plane defined by the two pions coming from the ρ decay).

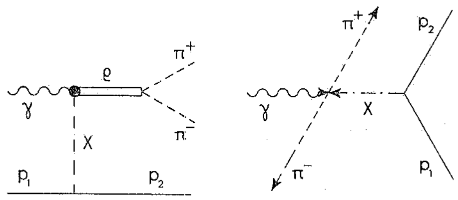
([41]) S. M. BERMAN and S. D. DRELL: *Phys. Rev.*, **133**, B 791 (1964); S. D. DRELL: *Proceedings of the International Symposium on Electron and Photon Interactions at High Energies*, vol. **1** (Hamburg, 1965), p. 71.

([42]) D. AMATI, S. FUBINI and A. STANGHELLINI: *Nuovo Cimento*, **26**, 896 (1962).

2) The OPE angle. The angle between the incident photon and the positive pion measured in the rest frame of the ρ.

3) The Adair angle. The angle between the direction of the incident photon in the laboratory system and the direction of the positive pion in the rest frame of the ρ.

The distribution of events as a function of the Treiman and Yang angle yields some information on the spin of the exchanged particle in peripheral models. To better understand its physical meaning we have to consider the event in the ρ center-of-mass system. In this system the peripheral graph at the left can be represented as indicated at the right.



It is clear that in the laboratory system the production plane will contain particles p_1, p_2, γ, ρ and the exchanged particle X. The decay plane will contain particles π^+, π^- and ρ. In this system the ρ is the only particle common to the two planes. In the center-of-mass system of the ρ the decay plane contains particles π^+, π^-, γ and X while the production plane contains p_1, p_2, γ, and X. In this system particles γ and X are collinear and therefore they are both common to the two planes. It is now easy to understand that if the exchanged particle X has no spin, all possible orientations of the decay plane with respect to the production plane are equally probable. In fact it is not possible to define any preferential direction perpendicular to the momentum of the exchanged particle.

The results of CEA for the angular distributions in the T-Y angle are indicated in Fig. 25 for different values of the primary-γ-ray energy. These results indicate an uniform distribution and therefore are consistent with a one-pion exchange model.

The angular distribution of the pions with respect to the direction of the incident γ-ray in the center-of-mass system of the ρ constitutes an even stronger test of the OPEM. It is clear from the previous diagram that if particle X has no spin then the angular momentum state of the ρ will be that of the incident photon, *i.e.* a particle of spin one with only two possible directions of polarization which are equally probable. This defines the angular distribution of the decay pions.

In general we can write the angular distribution for the decay pions in the ρ rest frame as a function of the OPE angle $\bar{\theta}$ and the T-Y angle φ as

$$W(\cos\bar{\theta}) = \frac{3}{4}(1-\varrho_{0,0})\left[1+\frac{3\varrho_{0,0}-1}{1-\varrho_{0,0}}\cos^2\bar{\theta}\right],$$

$$2\pi W(\varphi) = 1-2\varrho_{1,-1}\cos 2\varphi\,,$$

where $\varrho_{0,0}$ and $\varrho_{1,-1}$ are spin-density matrix elements which can be calculated according to the various photoproduction models. The results of the theoret-

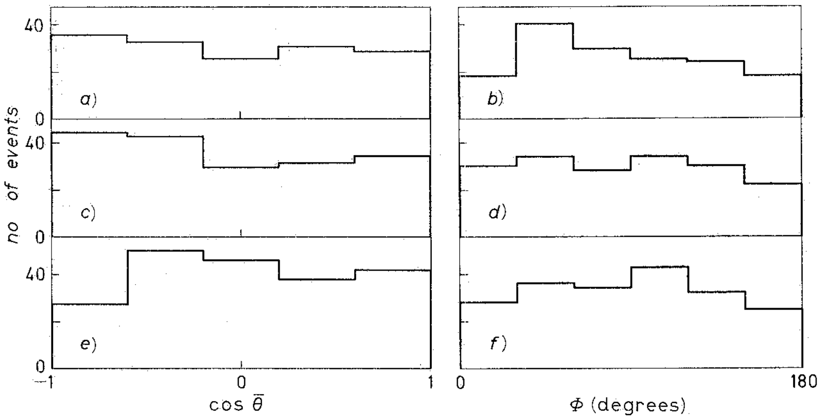


Fig. 25. – Angular distributions of the OPE angle $\bar{\theta}$ and the Treiman and Yang angle Φ for the ρ decay. CEA results. *a*) and *b*) $p_\gamma = (1.5 \div 1.8)$ GeV/c, *c*) and *d*) $p_\gamma = (1.8 \div 2.5)$ GeV/c, *e*) and *f*) $p_\gamma = (2.5 \div 6.0)$ GeV/c.

ical calculations and of the values obtained from a best fit of the experimental data of ref. ([11]) are included in Table V.

TABLE V.

Theoretical			Experimental	
E_γ (GeV)	$C=0$	$C=1$	All t	$t \leqslant 20m_\pi^2$
	$\varrho_{0,0}$		$\varrho_{0,0}$	
$1.5 \div 1.8$	0	0.16	0.36 ± 0.05	0.30 ± 0.07
$1.8 \div 2.5$	0	0.14	0.38 ± 0.05	0.34 ± 0.07
$2.5 \div 6.0$	0	0.13	0.24 ± 0.07	0.24 ± 0.07
	$\varrho_{1,-1}$		$\varrho_{1,-1}$	
$1.5 \div 1.8$	0	0.015	0.14 ± 0.07	0.12 ± 0.08
$1.8 \div 2.5$	0	0.02	0.10 ± 0.07	0.12 ± 0.08
$2.5 \div 6.0$	0	0.02	0.10 ± 0.04	0.08 ± 0.05

The theoretical calculations were based on a OPEM without final state interaction ($C = 0$) and with final state interaction ($C = 1$). The experimental data of CEA are indicated in Fig. 25. Those of DESY ([12]) in Fig. 26.

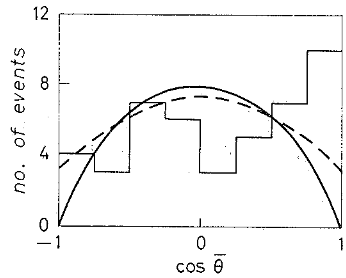


Fig. 26. – Angular distribution of the OPE angle for the ρ decay. DESY results. Solid line: OPEM without absorption; broken line: OPEM with absorption ($c = 1$). $\Delta^2 < 0.3\ (\text{GeV}/c)^2$.

For ρ photoproduced in the forward direction the Adair angle α, previously defined, is the same as the OPE angle $\bar{\theta}$ just mentioned. In this case the helicity of the ρ will be the same of that of the incident photon if no spin-flip occurs on the target nucleon. Therefore the decay angular distribution of the pions in the rest system of the ρ with respect to the direction of the γ-ray in the laboratory will be given by $\sin^2(\alpha)$. This conclusion is independent of the OPEM and is based only on the hypothesis that the nucleon does not flip its spin. For ρ's emitted at a small forward angle we can still apply the same reasoning if the decay angle of the pions is still measured with respect to the direction of the photon spin. In Fig. 27 we have indicated the distribution of the Adair angle as obtained in ref. ([11]). The results are consistent with a

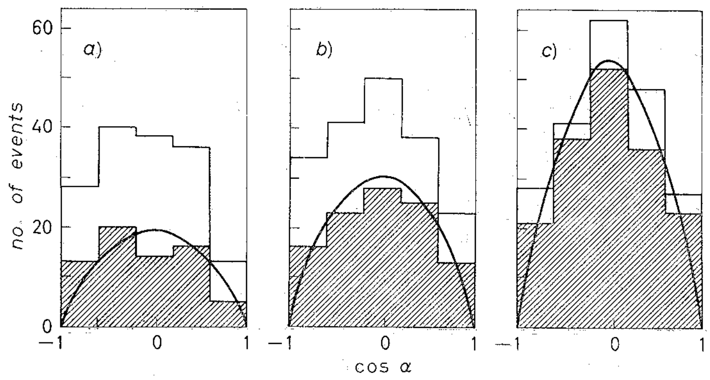


Fig. 27. – Angular distributions of the Adair angle α. The hatched area corresponds to events produced within $\cos\theta^0_{c.m.} \geqslant 0.85$. $a)$ $p_\gamma = (1.5 \div 1.8)$ GeV/c, $b)$ $p_\gamma = (1.8 \div 2.5)$ GeV/c, $c)$ $p_\gamma = (2.5 \div 6.0)$ GeV/c.

$\sin^2(\alpha)$ distribution and indicate a production process with no spin-flip. This could be interpreted either as the effect of a OPEM or a diffraction mechanism.

c) *ω-meson.* ω photoproduction in hydrogen has been seen in the bubble chamber experiments of CEA ([11]) and DESY ([12]). The first important experimental result is the fact that omegas are photoproduced less copiously than ρ by approximately a factor of five. The second is the strong forward peaking of the angular distribution of the ω in the center-of-mass system of the reac-

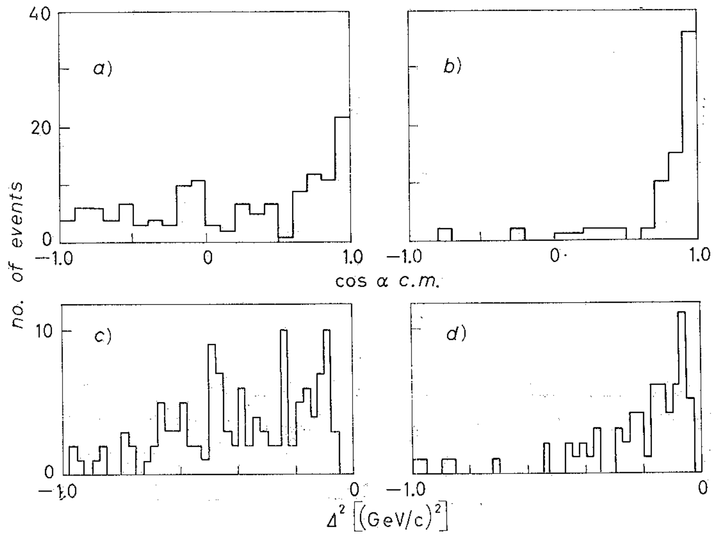


Fig. 28. – Differential cross-section for the reaction $\gamma+p\to p+\omega^0$ as a function of the omega angle α in the c.m.s. (top) and of the four-momentum transfer (bottom). $m(\pi^+\pi^-\pi^0)=(0.75\div0.825)$ GeV. *a*) $E_\gamma=(1.1\div1.8)$ GeV, 137 events; *b*) $E_\gamma=(1.8\div6.0)$ GeV, 76 events; *c*) $E_\gamma=(1.1\div1.8)$ GeV; *d*) $E_\gamma=(1.8\div6.0)$ GeV.

tion. The experimental information presently available on this process is summarized in Fig. 28 and 29. Fig. 28 represents the value of the total cross-section compared with different production models as OPEM and diffraction model. Figure 29 indicates the results of CEA for the differential cross-section as function of the momentum transfer.

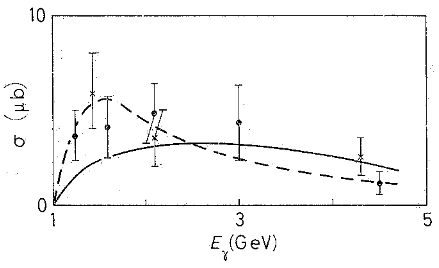
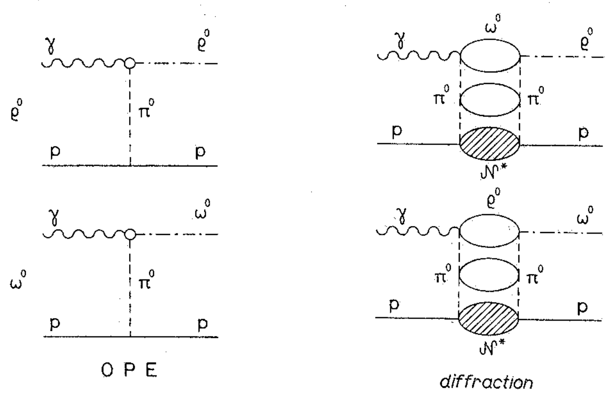


Fig. 29. – Total cross-section for the process $\gamma+p\to p+\omega^0$. The experimental points are compared with the theoretical predictions of the diffraction model (solid line) and the OPEM (broken line). • DESY ([12]), × CEA ([11]).

d) *Comparison between* ρ *and* ω *photoproduction.* The different behaviour of the cross-section for the photoproduction of vector mesons can be easily understood if we compare the following representative graphs for the diffraction and OPE models.



According to the various models we can easily write down the total cross-sections for the two processes as proportional respectively to:

	OPE	Diffraction
$\sigma_{tot}(\rho^0)$	$\Gamma_{\rho\pi\gamma}$	$\Gamma_{\omega\pi\gamma}$
$\sigma_{tot}(\omega^0)$	$\Gamma_{\omega\pi\gamma}$	$\Gamma_{\rho\pi\gamma}$

were $\Gamma_{\rho\pi\gamma}$ is the width for the $\rho\to\pi+\gamma$ decay and $\Gamma_{\omega\pi\gamma}$ is that for the $\omega\to\pi+\gamma$ decay.

It can now be immediately pointed out that $\Gamma_{\rho\pi\gamma}$ should be smaller than the other because it does not conserve the Bronzan-Low A quantum number ([43]). The same result can be predicted on the basis of SU_6 ([44]).

It is now obvious from the preceding table that if $\Gamma_{\rho\pi\gamma}<\Gamma_{\omega\pi\gamma}$ then we should have

$$\sigma_{tot}(\rho^0)<\sigma_{tot}(\omega^0)\,, \qquad \text{for OPE,}$$

$$\sigma_{tot}(\rho^0)>\sigma_{tot}(\omega^0)\,, \qquad \text{for diffraction.}$$

This is further evidence that the photoproduction of ρ mesons is mostly due to a diffraction mechanism. On the other side, ω photoproduction is probably produced through diffraction and OPE.

([43]) J. B. BRONZAN and F. E. LOW: *Phys. Rev. Lett.*, **12**, 522 (1964).

([44]) M. ROSS and L. STODOLSKY: *Phys. Rev.*, **149**, 1172 (1966); U. MAOR and P. C. M. YOCK: *Phys. Rev.*, **148**, 1542 (1966).

e) Other possible meson states. Some evidence has been found for possible pion resonances with a mass lower than the η mass. However this evidence is still very controversial. The largest amount of data is available for the ABC and the σ mesons. A large fraction of this data comes from photoproduction experiments. Here we will give a brief review of the main results.

1) ABC. This name has been given to an enhancement in the cross-section for 2π production at low energy. This enhancement was first reported by a Berkeley group ([45]) studying the energy spectrum of ^3He produced in the reaction

$$p+d \to {}^3He+X^0\,,$$

initiated by 740 MeV protons in deuterium. The bump found by these authors should correspond to a resonance with a mass of 320 MeV. The nonexistence of a similar bump in the reaction

$$p+d \to {}^3H+X^+$$

indicated that the isotopic spin of this state had to be zero.

This phenomenon has successively been looked for with other production mechanisms and in particular photoproduction experiments. Tentative evidence has been found by B. RICHTER ([46]) detecting the recoil proton in pion photoproduction as a function of the primary-γ-ray energy. Negative evidence of the same effect has been found by other authors ([47]).

2) σ-meson. We have at present some evidence favouring the existence of a resonant S-wave pion-pion interaction at an energy of approximately 400 MeV. Indications of the possible existence of this state come from the spectrum of the pions in the decay of the η^0 ([48]). BROWN and SINGER ([49]) suggested a resonance with quantum numbers $I^G J^P = 0^+0^+$ to explain the η^0 decay and the partial rates for the K_{e4} decay. The existence of a resonance with the same quantum numbers and a mass ranging from $(350 \div 400)$ MeV

([45]) A. ABASHIAN, N. E. BOOTH and K. M. CROWE: *Phys. Rev. Lett.*, **5**, 258 (1960); **7**, 35 (1961); *Rev. Mod. Phys.*, **33**, 393 (1961); A. ABASHIAN, N. E. BOOTH, K. M. CROWE, R. E. HILL and E. H. ROGERS: *Phys. Rev.*, **132**, 2296 (1963).

([46]) B. RICHTER: *Phys. Rev. Lett.*, **9**, 217 (1962).

([47]) C. BERNARDINI, R. QUERZOLI, G. SALVINI, A. SILVERMAN and G. STOPPINI: *Nuovo Cimento*, **14**, 268 (1959); R. GOMEZ, H. BURKHARDT, M. DAYBELL, H. RUDERMAN, M. SANDS and R. TALMAN: *Phys. Rev. Lett.*, **5**, 170 (1960); K. BERKELMAN, G. CORTELLESSA and A. REALE: *Phys. Rev. Lett.*, **6**, 234 (1961).

([48]) F. S. CRAWFORD jr., R. A. GROSSMAN, L. J. LLOYD and L. R. PRICE: *Phys. Rev. Lett.*, **11**, 564 (1963).

([49]) L. M. BROWN and P. SINGER: *Phys. Rev. Lett.*, **8**, 460 (1962); *Phys. Rev.*, **133**, B 812 (1964).

has also been suggested [50] to explain the nucleon and the α-α interaction. Some tentative evidence for this resonance has also been found [51] in the two-pion-mass spectra from reactions of the type

$$\gamma+p\to\mathcal{N}+n\pi\,.$$

One photoproduction experiment performed at Frascati [52] indicated some enhancement in the center-of-mass energy of the two pions in the reaction

$$\gamma+p\to p+\pi^{+}+\pi^{-}\,.$$

The proton and the two pions were detected in coincidence using spark chambers and counters. The interpretation of the enhancement found in this experiment is difficult because its energy position does not appear independent from the various possible kinematical configurations.

* * *

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Note added in proofs.

The definitive results of the German Bubble Chamber collaboration [53] based on the analysis of 800 000 pictures confirm substantially the preliminary results [12] and do not invalide the conclusions of the present work. Some evidence for f and X^0 resonance are reported and are resumed in a table:

	E_γ (GeV)	σ (μb)
f	2.5 ÷ 3.5	2.5 ± 1.3
	3.5 ÷ 5.8	0.6 ± 0.4
X^0	1.7	2.3 ± 1.1
	2.2	0.68 ± 0.52
	3.3	0.31 ± 0.21

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(50) S. FURUICHI: *Nuovo Cimento*, **39**, 279 (2965).

(51) N. P. SAMIOS, A. H. BACHMAN, R. M. REA, T. E. KALOGEROPOULOS and W. D. SHEPARD: *Phys. Rev. Lett.*, **9**, 139 (1962).

(52) R. DEL FABBRO, M. DE PRETIS, R. JONES, G. MARINI, A. ODIAN, G. STOPPINI and L. TAU: *Phys. Rev. Lett.*, **12**, 674 (1964).

(53) GERMAN BUBBLE CHAMBER COLLABORATION: DESY, report 66/32; *Phys. Lett.*, **23**, 707 (1966).