

Laboratori Nazionali di Frascati

LNF-66/61

C. Bacci, G. Penso, G. Salvini, C. Mencuccini and V. Silvestrini:  
 $\eta$  PHOTOPRODUCTION CROSS-SECTION FOR INCIDENT PHO-  
TON ENERGIES FROM 800 TO 1000 MeV. -

Nuovo Cimento 45, 983 (1966)

## $\eta$ Photoproduction Cross-Section for Incident Photon Energies from 800 to 1000 MeV.

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(ricevuto il 9 Maggio 1966)

**Summary.** — Photoproduction cross-section of the  $\eta$ -particle for incident photon energies  $K$  from  $\sim 800$  to  $\sim 1000$  MeV has been measured at the 1.1 GeV Frascati electronsynchrotron. The differential cross-section for this process, at a c.m. angle of the  $\eta$  of  $\sim 110^\circ$ , turns out to be fairly constant for  $830 \text{ MeV} \leq K \leq 900 \text{ MeV}$ , and drops down by a factor 5 to 10 at  $K = 950 \text{ MeV}$ . These results are discussed in terms of a comparison with the data on the production of  $\eta$ 's by pions, and with the data on pion-nucleon scattering and pion photoproduction. The conclusions are in agreement with the hypothesis that the  $\eta$ - $N$  system is dominated at low energies by a resonance with orbital angular momentum  $l=0$  ( $S_{\frac{1}{2},\frac{1}{2}}$  resonance).

### Introduction.

In this paper we describe an experiment which has been carried out during the last year at the 1.1 GeV Frascati electronsynchrotron, in order to measure the differential cross-section for photoproduction of the  $\eta$ -particle in the reaction

$$(1) \quad \gamma + p \rightarrow \eta + p.$$

The experimental results have been already synthetically presented elsewhere <sup>(1)</sup>.

In Sect. 1 we describe the experimental lay-out. The criteria used in the analysis of the data are discussed in Sect. 2. The experimental results are presented in Sect. 3, along with a discussion of possible sources of errors. In Sect. 4 we compare our results with the results on  $\eta$  production by pions, as well as with pion-nucleon scattering and pion photoproduction. Our conclusions are presented in Sect. 5.

### 1. - Experimental arrangement.

The experimental lay-out is shown in Fig. 1. It is similar in principle to the one used in our previous experiment <sup>(2)</sup>, which has been described in detail in ref. <sup>(3)</sup>, but it has now a much larger acceptance and better resolution.

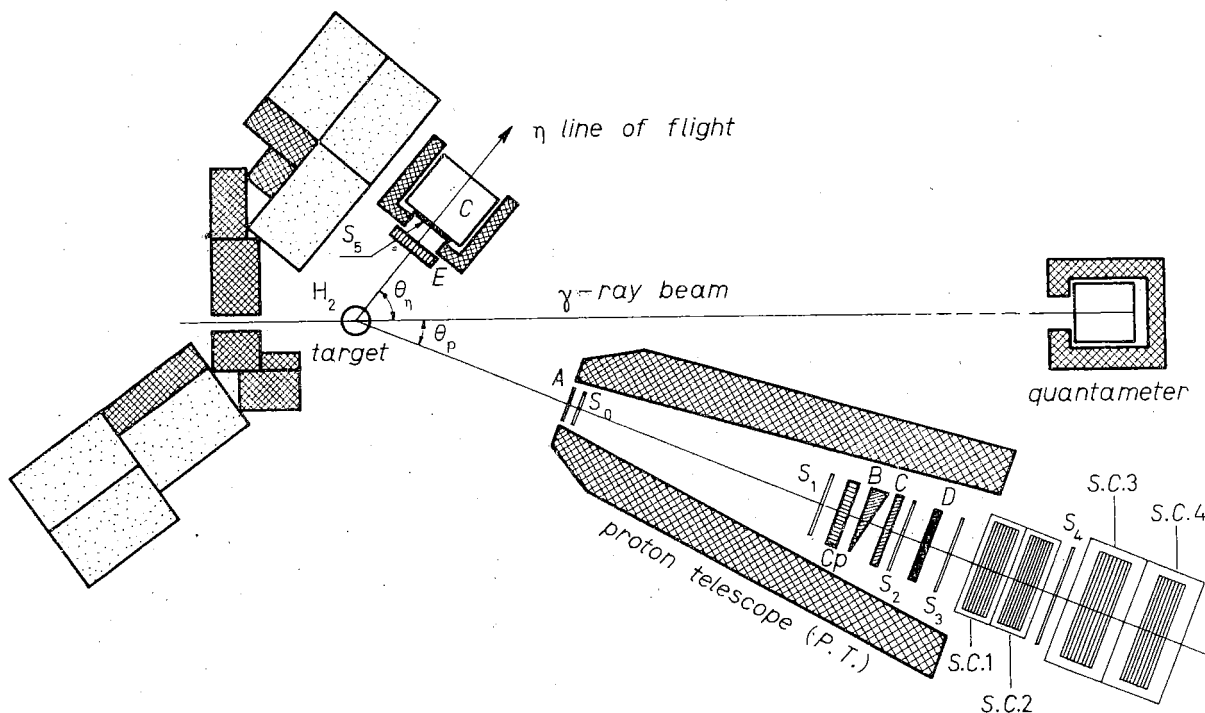


Fig. 1. - Experimental lay-out (see Table I). ▨ Pb, ▩ Al, ▤ concrete, ▥ polythene, ▦ plexiglass, ■ Cu.

<sup>(1)</sup> C. BACCI, G. PENSO, G. SALVINI, C. MENCUCCINI and V. SILVESTRINI: *Phys. Rev. Lett.*, **16**, 157, 384 (1966). See also: *Proceedings of the International Symposium on Electron and Photon Interactions at High Energies*, Hamburg, June 1965.

<sup>(2)</sup> C. BACCI, G. PENSO, G. SALVINI, A. WATTENBERG, C. MENCUCCINI, R. QUERZOLI and V. SILVESTRINI: *Phys. Rev. Lett.*, **11**, 37 (1963).

<sup>(3)</sup> C. BACCI, G. PENSO, G. SALVINI, A. WATTENBERG, C. MENCUCCINI, R. QUERZOLI and V. SILVESTRINI: Laboratori Nazionali di Frascati, Internal Report LNF 64/6 (1964).

The main point in our arrangement is to detect the recoil proton in the proton telescope P.T. (measuring its angle and energy), and the  $\gamma$ -rays from neutral decays of the  $\eta$  in the Čerenkov  $C$  (measuring their energy).

The Čerenkov  $C$  is set on the line of flight of the  $\eta$ . The kinematical situation with the specific values of  $\theta_p$  (angle of emission of the proton in the lab.) and  $\theta_\eta^*$  (angle of emission of the  $\eta$  in the c.m.s.) is given in Fig. 2.

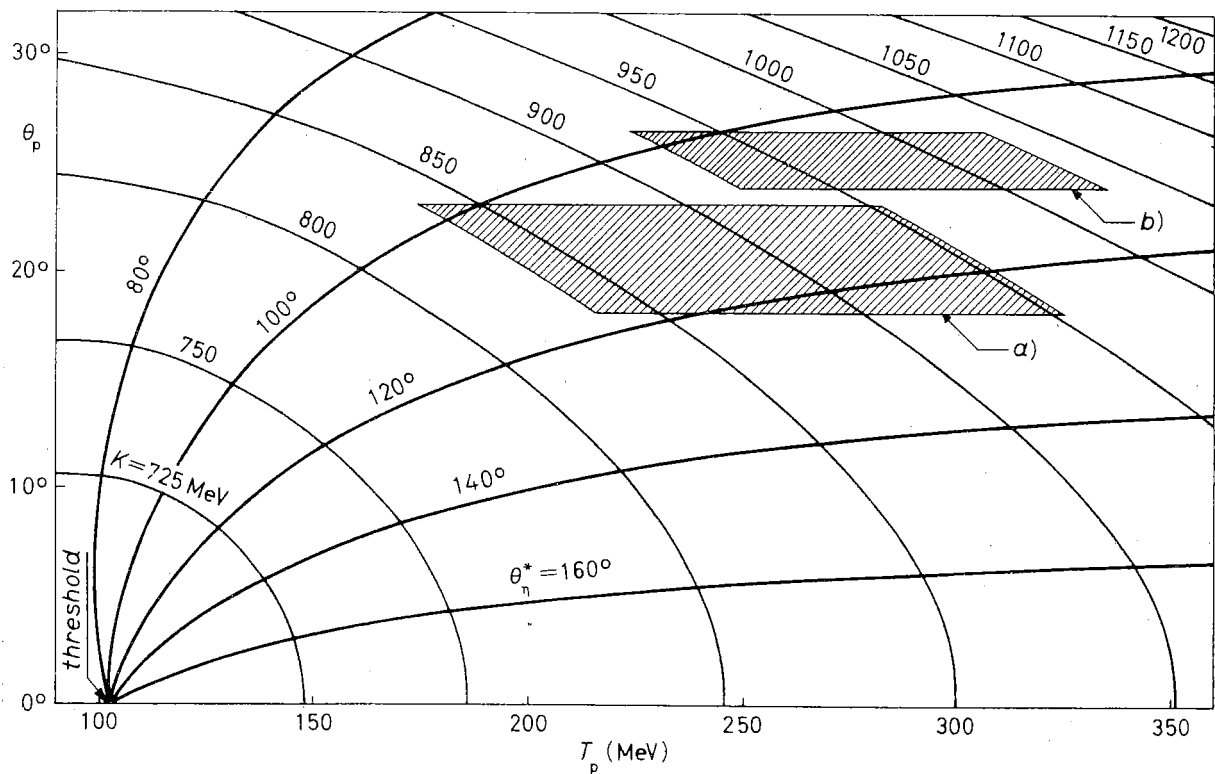


Fig. 2. — Kinematics of reaction (1): laboratory proton angle ( $\theta_p$ ) vs. laboratory proton kinetic energy ( $T_p$ ). Curves parameters: incident photon laboratory energy ( $K$ ) and c.m. angle of the  $\eta$  ( $\theta_\eta^*$ ). The shaded areas represent the kinematical situations chosen in the present  $a$ ), and in our previous ( $^2$ ) experiment  $b$ ).

The  $\gamma$ -ray beam from the Frascati 1.1 GeV electronsynchrotron is incident upon a 7.4 cm liquid-hydrogen target ( $^4$ ). The proton telescope (Fig. 1) consists in the scintillators  $S_0$  to  $S_4$ , the plexiglass Čerenkov counter  $Cp$ , and the four spark chambers S.C.1 to S.C.4. This telescope measures the energy of the recoil proton through their range in the spark chambers, and discriminates against pions and electrons. The  $\gamma$ -telescope (total absorption lead-glass Čerenkov counter  $C$  with an anticoincidence  $S_5$  in front) which detects  $\gamma$ -rays in coincidence with the protons, measures their energy through the pulse height.

( $^4$ ) V. MONTELATICI: *Nucl. Inst. and Meth.*, **29**, 121 (1964); and Laboratori Nazionali di Frascati, Internal Report LNF 62/20 (1962).

TABLE I. - Characteristics of counters and absorbers.

Distance from H <sub>2</sub> target (cm)	Counter or absorber (Fig. 1)	Material	Dimensions	Phototubes No. Type
Proton telescope				
98	A	Al plate	8 mm thick	
100	S <sub>0</sub>	plastic scintillator	(15 × 15 × 0.5) cm <sup>3</sup>	1 Philips 56 AVP
215	S <sub>1</sub>	plastic scintillator	(23 × 23 × 1.25) cm <sup>3</sup>	1 Philips 56 AVP
225	Op	plexiglass Čerenkov	(25 × 25 × 5.6) cm <sup>3</sup>	4 Philips 56 AVP
235	B	Al wedge	12 mm medium thickness	
245	C	Al plate	adjustable thickness	
249	S <sub>2</sub>	plastic scintillator	(23 × 23 × 2.5) cm <sup>3</sup>	2 Philips 56 AVP
259	D	Cu plate	3 mm thick	
269	S <sub>3</sub>	plastic scintillator	(22 × 22 × 1) cm <sup>3</sup>	1 Philips 56 AVP
282 (first plate)	S.C.1+S.C.2	(13 + 13) Al plates (spark chambers)	(13 + 13)((31.5 × 31.5 × 0.3) cm <sup>3</sup> )	
315	S <sub>4</sub>	plastic scintillator	(35 × 35 × 1.2) cm <sup>3</sup>	1 Philips 56 AVP
330 (first plate)	S.C.3+S.C.4	(13 + 13) Al plates (spark chambers)	(13 + 13)((41.5 × 41.5 × 0.3) cm <sup>3</sup> )	
γ-ray telescope				
35	E	polythene	25 cm diameter, 6 cm thick	
45	S <sub>5</sub>	plastic scintillator	(27 × 27 × 1.2) cm <sup>3</sup>	1 Philips 56 AVP
50	C	lead glass cylinder (total-absorption Čerenkov)	30 cm diameter, 25 cm thick	3 Philips 58 AVP

The proton telescope, the  $\gamma$ -ray telescope and the block diagram of the electronics are described in the following. A list of the characteristics of counters, absorbers and spark chambers is given in Table I.

1.1. *The proton telescope.* — The proton telescope (Fig. 1) is centered at an angle  $\theta_p = 20.6^\circ$  with respect to the incident photon beam direction and has an angular acceptance  $\Delta\theta_p = \pm 2.4^\circ$  corresponding to a solid angle, defined by counter  $S_3$ , of 6.7 msr in the laboratory system.

The elements of the proton telescope are (Fig. 1):

$S_0, S_1, S_2, S_3, S_4$ :	scintillation counters;
$Cp$ :	plexiglass Čerenkov counter;
$S.C.$ :	spark chambers;
$A, B, C$ :	aluminum absorbers;
$D$ :	copper absorber.

The spark chambers <sup>(5)</sup> are sandwiches of aluminium plates (3 mm thick), and glass frames (5.5 mm thick) glued with araldite. Henogal gas mixture (65% neon, 35% helium) is circulated in each chamber. A hole in each aluminium plate, at opposite corners for neighbouring plates, allows gas circulation through all the chambers. Each chamber has 13 aluminum plates (12 gaps); S.C.1 and S.C.2 are  $(31,5 \times 31,5)$  cm<sup>2</sup>; S.C.3 and S.C.4 are  $(41,5 \times 41,5)$  cm<sup>2</sup> useful area.

The spark chambers are driven by four spark-gaps in air, which are triggered when a coincidence of a «proton» with a  $\gamma$ -ray in  $C$  occurs.

A «proton» is defined by the coincidences:

$$N_1 = S_0(S_1 D) S_2 S_3 \bar{S}_4 \quad \text{or} \quad N_2 = S_0 S_1 S_2 S_3 S_4 \bar{C}p,$$

$\bar{S}_4$  and  $\bar{C}p$  being in anticoincidence.  $(S_1 D)$  means a discrimination on the pulse height of the counter  $S_1$ .

The triggering through  $N_1$  or  $N_2$  guarantees that all the protons stopping in the four spark chambers are counted. In fact  $N_2$  are particles entering S.C.3 and S.C.4 (Fig. 1). Since pions and electrons entering S.C.3 and S.C.4 are above the Čerenkov threshold in  $Cp$ , there is only a small contamination of them in  $N_2$ .

Conversely, pions stopping in S.C.1 and S.C.2 are often below threshold in  $Cp$ , which therefore has not been used in  $N_1$ . The discrimination on  $S_1$ ,

<sup>(5)</sup> C. BACCI, V. BIDOLI, G. SALVINI and M. SPINETTI: Istituto di Fisica, Università di Roma, Internal Report n. 66.

however, eliminates a good percentage of pions stopping in S.C.1 and S.C.2 without eliminating protons. The additional condition of a coincidence with a  $\gamma$ -ray in *C*, reduces to  $\sim 10\%$  the contamination of pions in the triggers of the spark chambers. Finally, the pulse heights in  $S_2$  and  $S_3$  are digitized and recorded on each photo: complete elimination of pions is then allowed, when analysing the data, by a two-dimensional pulse height plot for particles stopping in a small range interval (Fig. 3).

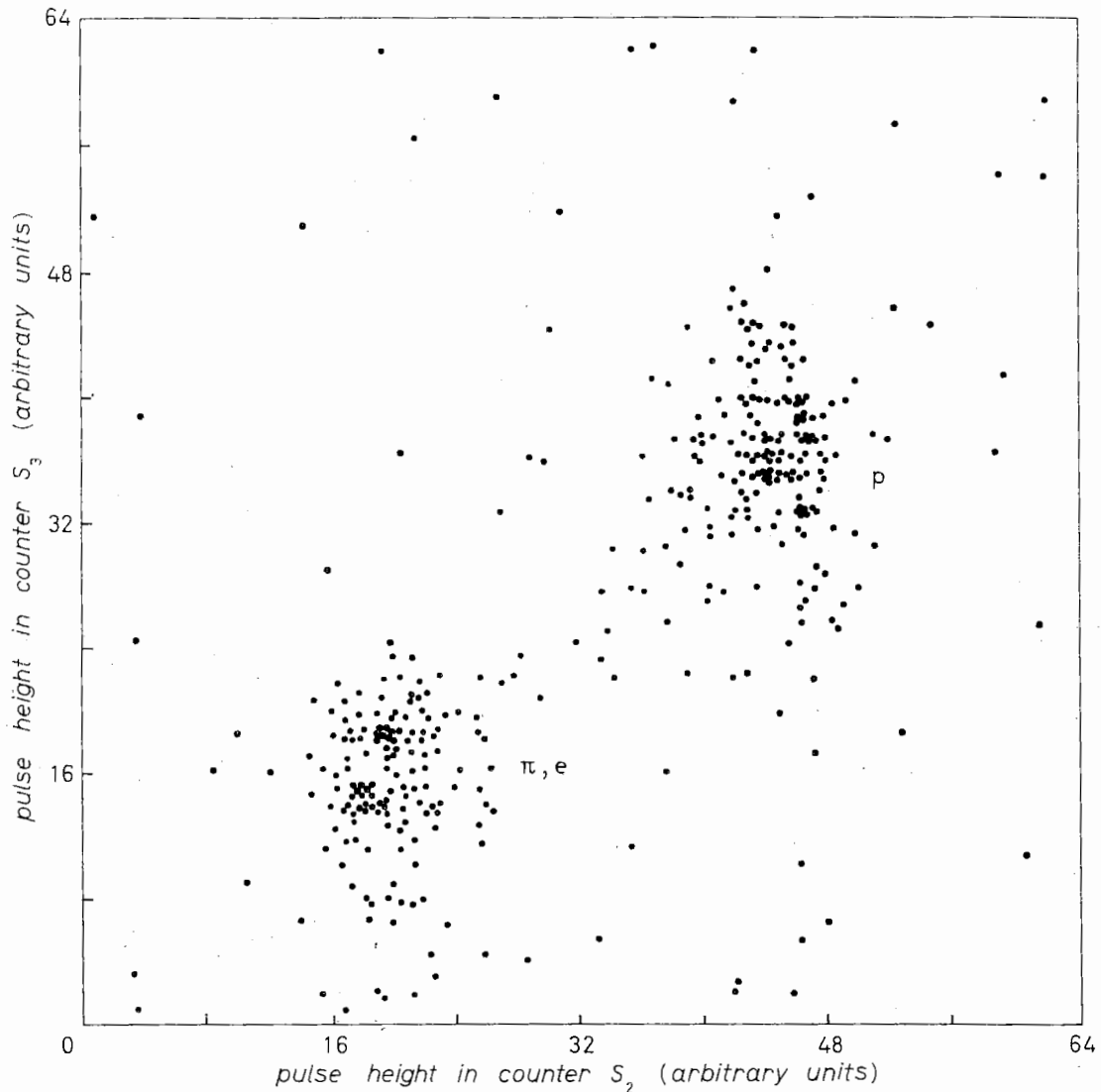


Fig. 3. — Bidimensional plot of pulse heights in counters  $S_2$  and  $S_3$ . Proton are clearly separated from electrons and pions.

The wedge-shaped aluminum absorber *B* in P.T. corrects for the dependence of the energy of the recoil protons from reaction (1) on their angle of emission. This allows a one-to-one correspondence between the energy of the incident photon and the stopping gap of the proton in S.C., simplifying the analysis of the data.

1'2. *The  $\gamma$ -ray telescope.* — The total-absorption Čerenkov counter  $C$  (Fig. 1) is a cylinder (30 cm in diameter, 25 cm thick) of lead glass manufactured by Schott (Jena), 60% in weight of Pb, with a radiation length of  $\sim 2.5$  cm; it is viewed by three 58 AVP phototubes.

The container of the phototubes, with their voltage dividers, is cooled with forced air circulation to avoid drifts due to changes in temperature.

A lead collimator in front of  $C$  (Fig. 1) reduces the useful area to 25 cm in diameter. The anticoincidence counter  $S_5$  is placed between the lead collimator and the Čerenkov. A slab ( $E$ ) of polythene 6 cm thick shields  $S_5$  from low-energy particles, to lower the rate of accidental anticoincidences.

The Čerenkov counter  $C$  was calibrated using monochromatic electrons from the Frascati pair spectrometer (<sup>6</sup>). The result of the calibration pulse (height analyser channel vs. electron energy) is shown in Fig. 4.

The resolution during the calibration turned out to be  $\sim \pm 20\%$  (half width at half maximum) at 500 MeV, changing as  $\sim 1/\sqrt{E}$  with the electron energy.

1'3. *The electronics.* — The block diagram of the electronics is shown in Fig. 5. Most of the elements used are described in ref (<sup>7</sup>). The part concerning the coincidence between the proton channel and the  $\gamma$ -ray channel has been duplicated in order to have a simultaneous measurement of the accidental rate which is, for the coincidence  $\gamma$ -proton, as high as  $\sim 10\%$ . The accidental rate in the proton channel is much smaller ( $(2 \div 3)\%$ ).

The pulse height spectrum of the Čerenkov counter  $C$  is measured in a multichannel analyser: the digitized output of the analyser is also recorded on each photo, which thus contains the following information: angle and energy of the proton from the spark chambers: we use the Berkeley range-energy tables (<sup>8</sup>) to get the kinetic energy of the proton; energy of the  $\gamma$ -ray in the Čerenkov  $C$ ; pulse heights in  $S_2$  and  $S_3$ .

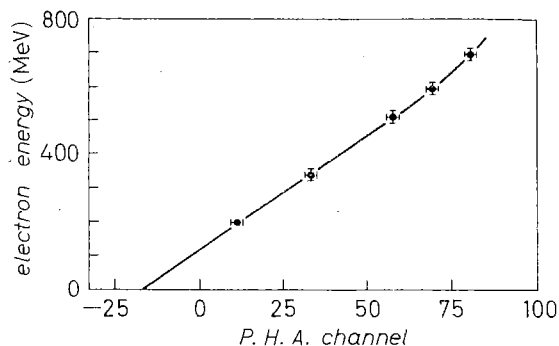


Fig. 4. — Results of the calibration of the lead glass Čerenkov  $C$ : energy of incident electrons vs. average pulse height analyser channel.

(<sup>6</sup>) G. BOLOGNA, G. DIAMBRINI and G. P. MURTAS: *Suppl. Nuovo Cimento*, **24**, 342 (1962).

(<sup>7</sup>) G. PENSO and V. SILVESTRINI: Laboratori Nazionali di Frascati, Internal Report LNF 64/45 (1964).

(<sup>8</sup>) M. RICH and R. MADEY: U.C.R.L. 2301 (1954).



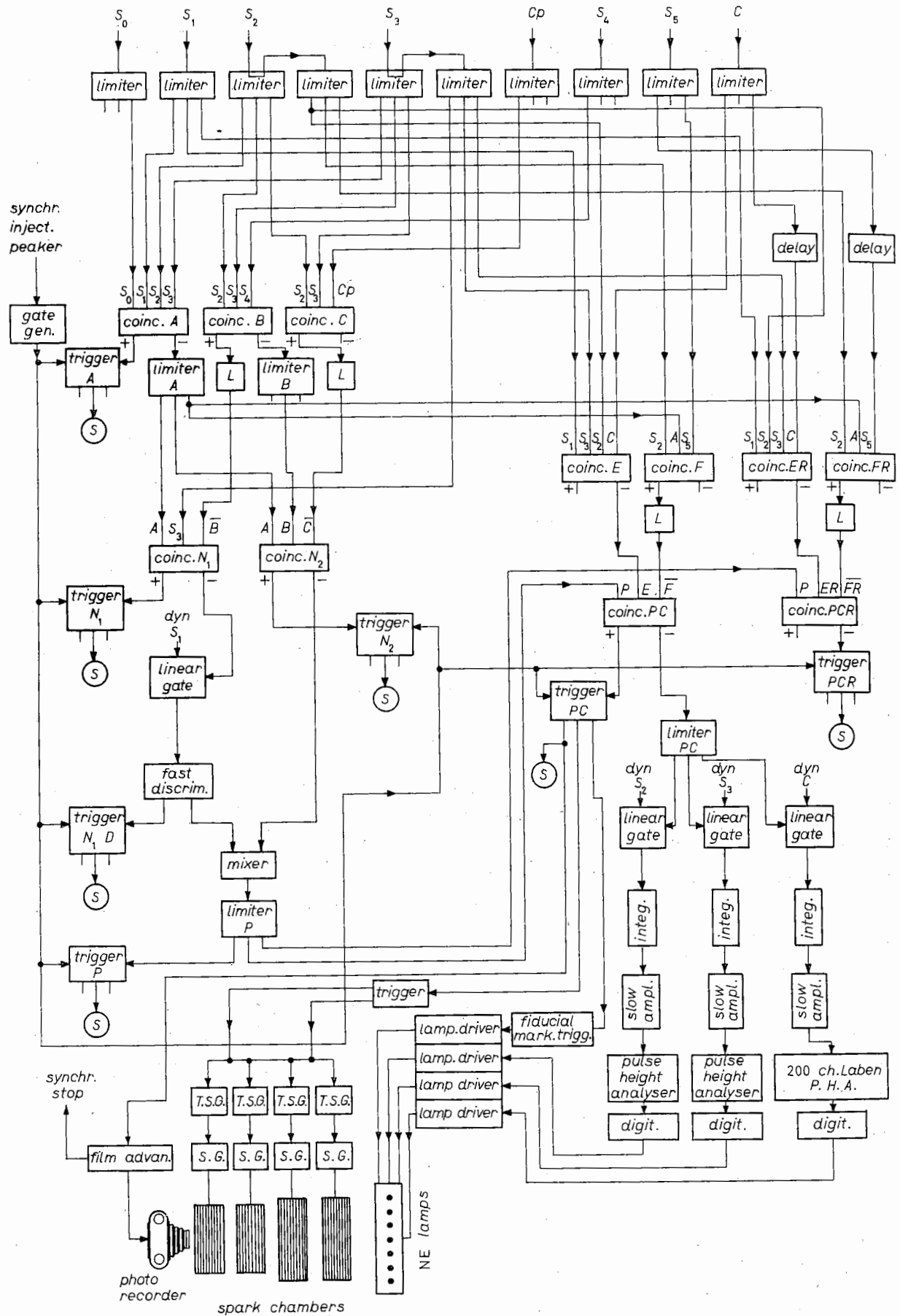
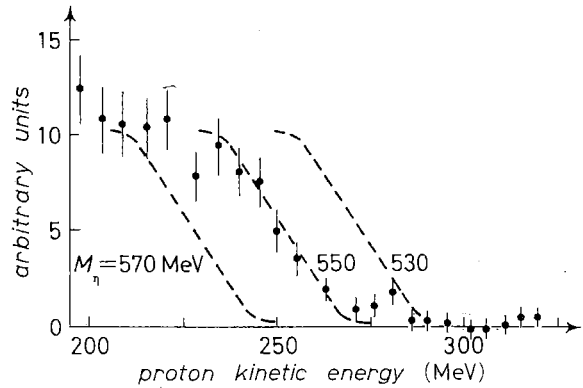


Fig. 5. - Block diagram of the electronics. *S* = scaler; *L* = fast pulse shaper; S.G. = spark gap; T.S.G. = trigger spark gap.

## 2. - Data reduction.

After the elimination of pions and electrons from the particles detected in P.T. our information is summarized in a bidimensional plot, whose co-ordinates are: the stopping-gap of the proton, that is a quantity which goes with the

Fig. 6. - A typical result of the step method: energy spectrum of protons in coincidence with a  $\gamma$ -ray in  $C$  with energy  $E_\gamma \geq 420$  MeV. The step characteristic of recoil protons from reaction (1) is clearly visible, overposed to a small background. The expected position of the step for different values of the mass of the  $\eta$  is shown. The machine energy ( $E_0$ ) was 900 MeV.



kinetic energy  $T_p$  of the proton; and the multichannel response to the Čerenkov  $C$ , that is a quantity going with the energy  $E_\gamma$  of the detected photon. When we

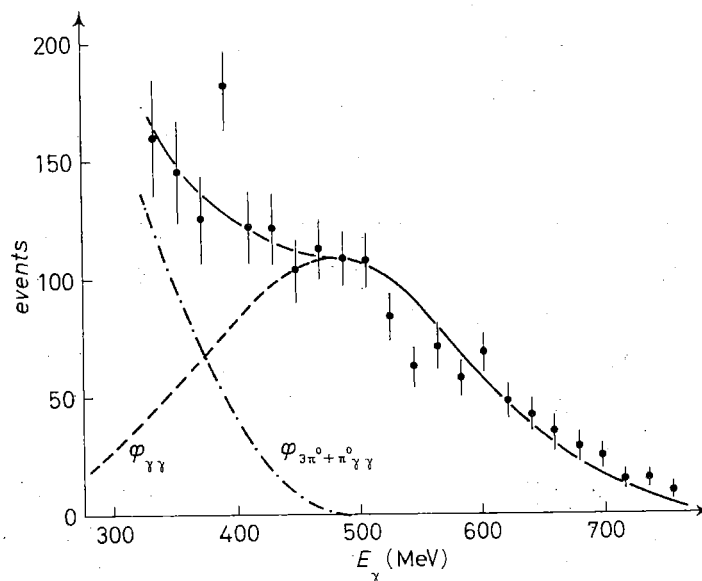


Fig. 7. - Result of the  $\gamma$ -ray method: energy spectrum of photons in  $C$  in coincidence with protons whose energy was compatible with being recoil protons from reaction (1). The spectrum is fitted with the expected shape for photons from the neutral decays of the  $\eta$ .

project this plot on the proton axis, we obtain the proton energy spectrum (Fig. 6); when we project on the  $\gamma$ -ray axis, we get the energy distribution of the  $\gamma$ 's (Fig. 7).

Both the photon spectra and the proton spectra contain useful information on reaction (1).

2.1.  $\gamma$ -ray spectra. — The  $\eta$  can undergo at least the following decay modes:

$$\eta \rightarrow \pi^+\pi^-\gamma, \quad \eta \rightarrow \gamma\gamma, \quad \eta \rightarrow \pi^0\gamma\gamma, \quad \eta \rightarrow \pi^+\pi^-\pi^0, \quad \eta \rightarrow 3\pi^0.$$

The expected energy spectra of photons entering  $C$  from the neutral decay modes of the  $\eta$  are shown in Fig. 8. They have been computed in the statistical

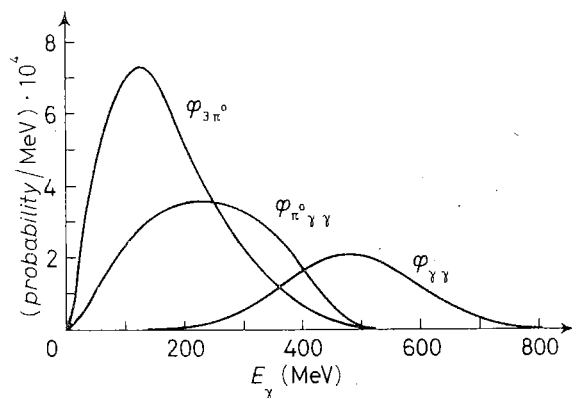


Fig. 8. —  $\gamma$ -ray energy spectra in  $C$  expected from the decays of the  $\eta$ . The calculation has been done in the statistical model. Experimental resolution is folded in. For spectra normalization see text.

model, using the Monte Carlo method. The finite dimensions of the counters and the energy resolution of the Čerenkov  $C$  have been taken into account. The spectra are normalized to equal probability for the different decay modes. Therefore the area

$$\int_0^{\infty} \varphi_i(E_\gamma) dE_\gamma$$

represents the efficiency of detection in  $C$  of the  $i$ -th decay mode ( $i$  stands for  $\gamma\gamma$ ,  $3\pi^0$ ,  $\pi^0\gamma\gamma$ ). As we see, the spectrum due to the decay mode  $\eta \rightarrow \gamma\gamma$  is quite different from the others: it is a peak whose width is determined practically only by the energy resolution of  $C$  and centered at an energy of 480 MeV, where the contribution from the other decay modes is rather small. The spectrum from background processes (multipion production) is very similar to the spectrum from the decay  $\eta \rightarrow 3\pi^0$ . The spectra of Fig. 8 refer to an incident-photon energy  $K = 900$  MeV, but they are quite insensitive to this parameter. Once an experimental  $E_\gamma$ -spectrum has been collected (referring to protons stopping in a small range interval, that is to a small  $K$  interval), the number of events due to reaction



can be extracted by fitting the spectrum with the curves of Fig. 8. This method is not very satisfactory, due to the rather poor resolution of the Čerenkov  $C$ . However, the results we got are in very good agreement with the results of the more powerful step method, which we are going to describe.

2.2. *Proton spectra.* — The energy spectrum of protons from reaction (1) is expected to be an image of the bremsstrahlung spectrum, weighted with the cross-section for process (1). Therefore it must show a step, corresponding to the end of the bremsstrahlung spectrum. The height of this step over the smooth spectrum of protons from background processes is proportional to the cross-section for process (1). The main difficulty of this method is that the step is generally very small, over the total contribution of background processes.

However, if we select protons in coincidence with high-energy photons in the Čerenkov  $C$  (for instance  $E_\gamma \geq 420$  MeV), it is clear from the spectra of Fig. 8 that not very much is left but the contribution of process (2). In fact, we get in this case proton spectra which are very close to pure steps, the contribution from background processes being quite small (Fig. 6).

This background has been evaluated on the following line: by collecting experimental data at many different values of the machine energy ( $E_0$ ), a systematic investigation of background processes is performed in the kinematical region just below threshold of  $\eta$  production at our angle. We then extrapolate in the region where the  $\eta$  is produced as described in detail in ref. (3). It is worth noticing however that the multipion background is less important in this experiment than in our previous one (2), since in the chosen kinematical region the cross-section for reaction (1) turned out to be a factor 5 to 10 higher than before, the multipion background being almost unchanged.

### 3. — Experimental results.

3.1. *Step method.* — A typical proton spectrum in coincidence with photons in the Čerenkov counter of energy  $\geq 420$  MeV, is shown in Fig. 6. The expected position of the step for different values of the mass of the  $\eta$  is also shown. As we see the background from processes other than process (1) is indeed very small. In Fig. 9 the difference between two proton spectra corresponding to different energies  $E_0$  of the electronsynchrotron (900 MeV and 860 MeV) is given. In this case, the spectrum is a peak, whose position corresponds to a

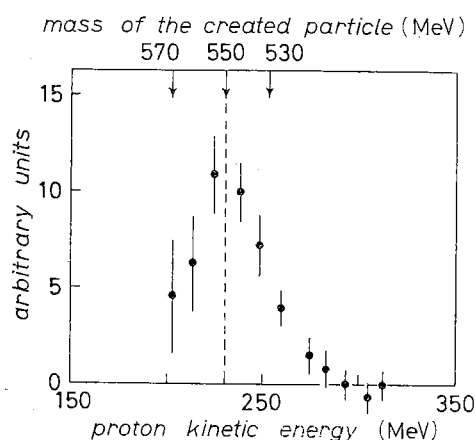


Fig. 9. — Typical result of the differentiation method: difference between two-proton energy spectra (in coincidence with photons of energy  $E_\gamma \geq 420$  MeV in  $C$ ) taken at different values of the machine energy ( $E_0 = 900$  MeV and  $E_0 = 860$  MeV). The expected position of the peak for different values of the mass of the  $\eta$  is shown (upper scale).

mass of the  $\eta$  of 550 MeV, with an error of a few MeV. The absolute calibration of the machine energy, and of the energy scale in the proton spectrum, was checked by making a similar step-spectrum from single  $\pi^0$  photoproduction <sup>(8)</sup>.

From the various spectra of the type shown in Fig. 6 one can calculate the cross-section for process (1):

$$(3) \quad \frac{d\sigma}{d\Omega^*} = \frac{n}{\varepsilon} \frac{\varepsilon_1 \varepsilon_2}{N_{H_2} N_\gamma \Delta\Omega^*},$$

where

- $d\sigma/d\Omega^*$  is the c.m. differential cross-section relative to a given c.m. angle  $\theta_\eta^*$  of emission of the  $\eta$  in reaction (1);
- $n$  is the number of  $\eta$  events observed in a given energy interval of the incident photons;
- $\varepsilon$  is the efficiency of detection of the  $\eta$  through its decay products.  $\varepsilon$  can of course be calculated once the spectra of Fig. 8 are known. The main source of error in  $\varepsilon$  comes from a possible error in the absolute calibration of  $C$ , affecting the energy cut-off at a nominal value of 420 MeV. A possible error of  $\pm 7\%$  in the energy calibration was propagated to  $\varepsilon$ . A factor of  $\sim 0.94$  was applied to the efficiency to correct for the absorption of  $\gamma$ -rays in the polythene in front of  $S_5$ .
- $N_{H_2}$  is the number of protons per  $\text{cm}^2$  in the  $H_2$  target. From the geometry of the liquid hydrogen target,  $N_{H_2}$  was evaluated with an estimated error of  $\pm 3\%$ .
- $\varepsilon_1 \varepsilon_2$  are correction terms which take into account the nuclear interactions and the Coulomb scattering in P.T., respectively.  $\varepsilon_1$  was evaluated using a mean free path for interaction in aluminium  $\lambda = 110 \text{ g/cm}^2$ , as extracted from MILLBURN *et al.* <sup>(9)</sup>. A possible error of  $\pm 20\%$  in  $\lambda$  was propagated to  $\varepsilon_1$ .  $\varepsilon_2$  was evaluated to be  $\sim 1$  in our telescope.
- $\Delta\Omega^* = (d\Omega^*/d\Omega)\Delta\Omega$  is the c.m. solid angle of the proton telescope. It was calculated from the geometry of the telescope, and checked by making a distribution of the events as a function of the entrance point in the spark chamber (Fig. 10). This checks also that  $\varepsilon_2 \simeq 1$ .
- $N_\gamma$  is the number of incident photons in the concerned energy interval.

<sup>(9)</sup> G. P. MILLBURN, W. BIRNBAUM, W. E. CRANDALL and L. SCHECTER: *Phys. Rev.*, **95**, 1268 (1954).

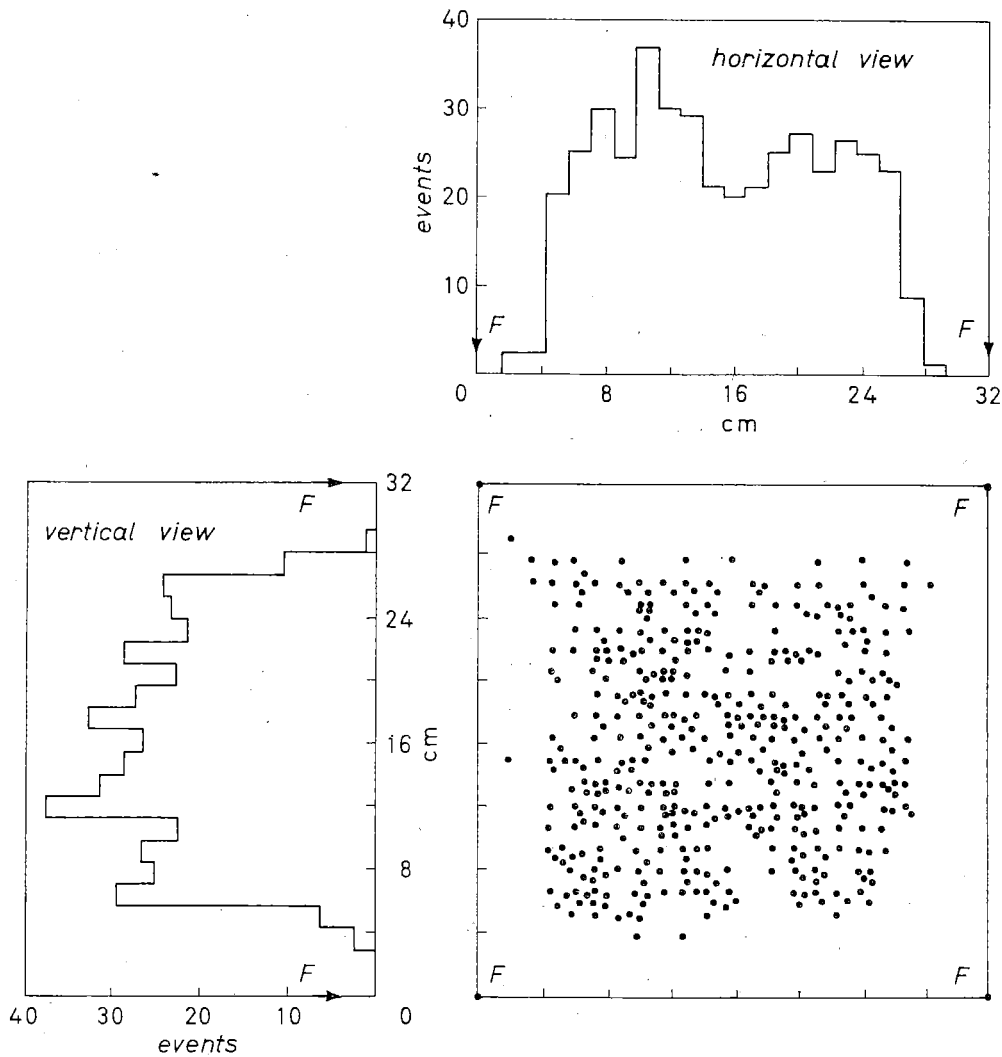


Fig. 10. — Distribution of protons entering S.C.1 as a function of the entrance co-ordinates. This distribution fits well with the shadow from the  $H_2$  target of counter  $S_3$ , which defines the solid angle. The fiducial marks  $F$  indicate the useful area of the spark chamber.

We have

$$N_\gamma = \frac{1}{K} b \left( \frac{K}{E_0} \right) \Delta K Q ,$$

where

- $(1/K)b(K/E_0)$  is the energy spectrum of the bremsstrahlung beam <sup>(10)</sup>;
- $\Delta K = (dK/dT_p)\Delta T_p$  is the accepted energy interval of the incident photons;
- $K$  is the average value of the energy of the accepted incident photons;

<sup>(10)</sup> G. DIAMBRINI, A. S. FIGUERA, B. RISPOLI and A. SERRA: *Nuovo Cimento*, **19**, 250 (1961).

—  $Q$  is the number of equivalent quanta measured with a Wilson quantameter <sup>(11)</sup>;

$N_\gamma$  was considered known with an error of  $\pm 5\%$ , due to a possible error in the calibration of the Wilson quantameter;

3.2.  $\gamma$ -rays method. — As we said, the number of events  $\eta \rightarrow \gamma\gamma$  is extracted from the  $\gamma$ -ray spectra by fitting the experimental spectra (Fig. 7) with the computed spectra of Fig. 8. The cross-section is then computed on the same lines as for the step method.

The results of the two methods are clearly not statistically independent. The consistency of the results obtained with the two methods (Fig. 11) checks against systematic errors in the extraction of  $\eta$ -events from background.

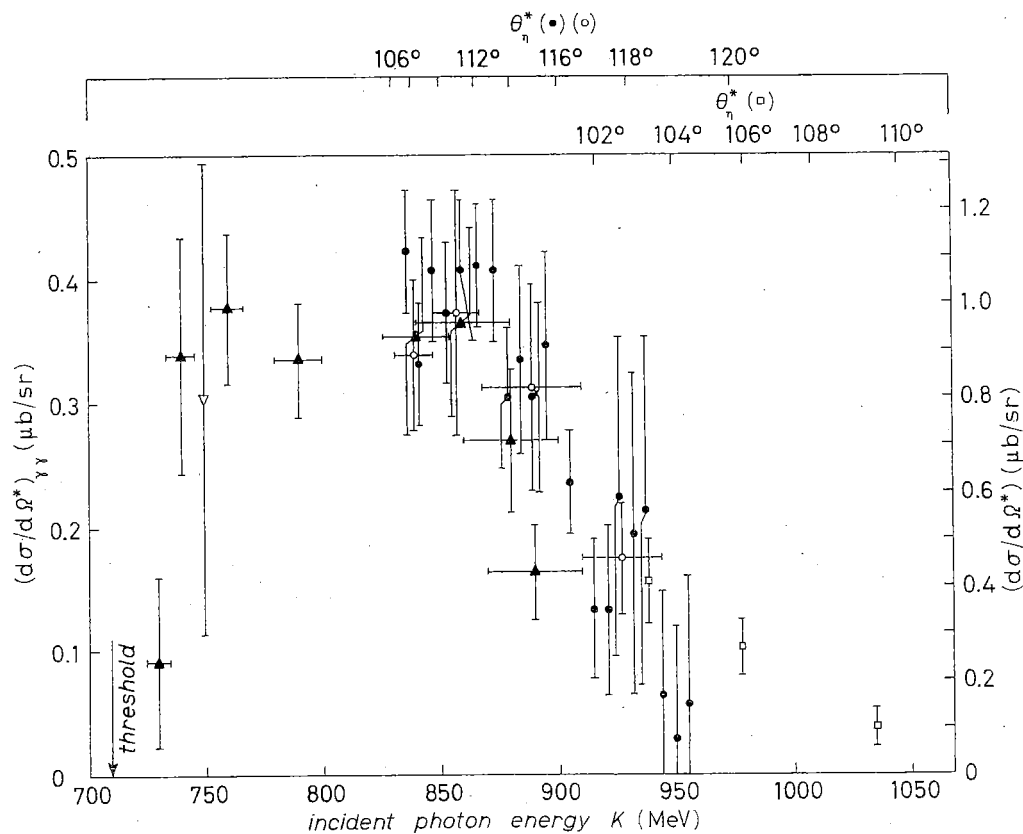


Fig. 11. — Experimental results on  $\eta$ -photoproduction cross-section around  $90^\circ \div 120^\circ$  c.m.s., available up to now:  $\bullet$  present results (step method);  $\circ$  present results ( $\gamma$ -ray method);  $\square$  Frascati 1963 <sup>(2)</sup>;  $\blacktriangle$  PREPOST *et al.* <sup>(12)</sup>;  $\triangle$  DELCOURT *et al.* <sup>(13)</sup>.

<sup>(11)</sup> R. R. WILSON: *Nucl. Instr. and Meth.*, **1**, 101 (1957).

<sup>(12)</sup> R. PREPOST, D. LUNDQUIST and D. QUINN: *Eta photoproduction in the region from threshold to 900 MeV*, in *Proceedings of the International Symposium on Electron and Photon Interactions at High Energies*, Hamburg, June 1965.

<sup>(13)</sup> B. DELCOURT, J. LEFRANÇOIS, J. P. PEREZ Y JORBA and J. K. WALKER: *Phys. Lett.*, **7**, 215 (1963).

TABLE II. - Differential cross-section for the process  $\gamma + p \rightarrow \eta + p$  as obtained with the step method.

$K$ (MeV)	$(d\sigma/d\Omega^*)_{\gamma\gamma}$ ( $10^{-31}$ cm <sup>2</sup> /sr)	$(d\sigma/d\Omega^*)$ ( $10^{-31}$ cm <sup>2</sup> /sr)	$\theta_\eta^*$ (deg.)
(1)	(2)	(3)	(4)
836	4.24 ± 0.51	11.1 ± 1.3	107
841	3.29 ± 0.51	8.7 ± 1.3	108
847	4.05 ± 0.59	10.7 ± 1.5	109
853	3.71 ± 0.59	9.8 ± 1.5	110
859	4.05 ± 0.59	10.7 ± 1.5	111
866	4.14 ± 0.51	10.8 ± 1.3	112
873	4.05 ± 0.59	10.7 ± 1.5	113
879	3.04 ± 0.59	8.0 ± 1.5	113
884	3.37 ± 0.76	8.8 ± 2.0	114
889	3.04 ± 0.76	8.0 ± 2.0	114
895	3.46 ± 0.76	9.1 ± 2.0	115
905	2.36 ± 0.42	6.2 ± 1.1	115
915	1.35 ± 0.59	3.5 ± 1.5	116
921	1.35 ± 0.68	3.5 ± 1.8	116
926	2.23 ± 1.30	5.9 ± 3.4	117
932	1.95 ± 1.30	5.1 ± 3.4	117
937	2.14 ± 1.40	5.6 ± 3.7	118
944	0.65 ± 0.84	1.7 ± 2.2	118
950	0.28 ± 0.93	0.74 ± 2.4	119
955	0.56 ± 1.02	1.5 ± 2.7	119

Col. (1): energy of the incident  $\gamma$ -ray, laboratory system.

Col. (2): differential cross-section in the c.m.s. relative to the  $\eta$  decaying in the mode  $\eta \rightarrow \gamma\gamma$ .

Col. (3): differential cross-section in the c.m.s. for  $\eta \rightarrow$  all modes ( $\Gamma_{\gamma\gamma}/\Gamma_{\text{tot}} = 0.38$  from the world average <sup>(14)</sup>).

Col. (4): Center-of-mass angle of the  $\eta$ .

TABLE III. - Differential cross-section for the process  $\gamma + p \rightarrow \eta + p$  ( $\gamma$ -rays method).  
For symbols see Table II.

$K$ (MeV)	$(d\sigma/d\Omega^*)_{\gamma\gamma}$ ( $10^{-31}$ cm <sup>2</sup> /sr)	$(d\sigma/d\Omega^*)$ ( $10^{-31}$ cm <sup>2</sup> /sr)
(1)	(2)	(3)
839 ± 8	3.38 ± 0.61	8.9 ± 1.6
857 ± 10	3.73 ± 0.63	9.8 ± 2.6
889 ± 21.5	3.13 ± 0.50	8.2 ± 2.2
927 ± 17.4	1.73 ± 0.47	4.6 ± 1.2

<sup>(14)</sup> A. H. ROSENFELD, A. BARBARO-GALTIERI, W. H. BARKAS, P. L. BASTIEN, J. KIRZ and M. ROOS: *Rev. Mod. Phys.*, **37**, 633 (1965).



3.3. *Results.* — In Table II (column 2) the results for the cross-section  $(d\sigma/d\Omega^*)$  ( $\eta \rightarrow \gamma\gamma$ ) are given (step method). In Table III (column 2) the values of this cross-section from the analysis of the  $\gamma$ -spectra are also given.

The values of the cross-section  $(d\sigma/d\Omega^*)$  for the process

$$\begin{array}{c} \gamma + p \rightarrow \eta + p \\ \downarrow \\ \text{all modes} \end{array}$$

reported in column 3 (Table II and III), are obtained by dividing the measured cross-section for  $\gamma + p \rightarrow \eta + p$ , by the branching ratio

$$\begin{array}{c} \downarrow \\ \gamma\gamma \\ \frac{\eta \rightarrow \gamma\gamma}{\eta \rightarrow \text{all modes}} \end{array}$$

which is known from the world average <sup>(14)</sup> as  $0.38 \pm 0.03$ .

In Fig. 11 we report  $(d\sigma/d\Omega^*)(\eta \rightarrow \gamma\gamma)$  (ordinates on the left) and  $(d\sigma/d\Omega^*)(\eta \rightarrow \text{all modes})$  (ordinates on the right).

In Table IV the photon flux used to collect each set of data is reported in equivalent quanta.

TABLE IV. — *Photon flux used to collect the data.* Different values of the machine energy were set during the measurements, in order to get a good evaluation of multipion background.

Machine energy $E_0$ (MeV)	Number of equivalent quanta
810	$18.6 \cdot 10^{12}$
860	$20.0 \cdot 10^{12}$
900	$31.0 \cdot 10^{12}$
940	$40.0 \cdot 10^{12}$
980	$19.9 \cdot 10^{12}$

#### 4. — Discussion of our results and comparison with other data.

4.1. — Let us first make some immediate comments on our values of the cross-section, reported in Fig. 11. The cross-section, at least at our angles, goes down rather drastically from  $K = 860$  MeV to 950 MeV. We know from the work of PREPOST *et al.* <sup>(12)</sup> that the cross-section for process (1) rises from threshold (710 MeV) rather abruptly and stays more or less at the same value from  $\sim 760$  MeV to  $\sim 860$  MeV. PREPOST *et al.* <sup>(12)</sup> also found that the cross-section is rather close to isotropy at  $\sim 800$  MeV.

The photoproduction of the  $\eta$  has therefore a fast rise and a rather fast decrease, which immediately invites to look for a resonant behaviour, or at least for the large phase-shift responsible for this anomaly.

This question goes to the fundamental aspects of the  $\eta$ -baryon system: in fact a similar behaviour (fast rise and rather fast descent), even if not so pronounced, is observed in the reaction  $\pi^- + p \rightarrow \eta + n$  by BULOS *et al.* <sup>(15)</sup>. Beyond this, such a behaviour of the  $\eta$  cross-section appears in a dramatic way in the  $\eta\Lambda$  system <sup>(16)</sup>. In fact in the reaction  $K^- + p \rightarrow \eta + \Lambda$  the total cross-section reaches its maximum at  $\sim 5$  MeV above threshold in the c.m.s. (this corresponds to a c.m. momentum of  $\sim 50$  MeV/c) and is again below one half of the maximum at  $\sim 25$  MeV above the threshold (that is about 140 MeV/c of the  $\eta$  c.m. momentum).

The  $\eta$  seems therefore ready to appear in all channels as soon as this is dynamically possible. On the contrary, when the c.m. energy increases, the  $\eta$  production goes down to much lower limits. In fact the  $\eta$  production is low in  $p\bar{p}$  annihilation <sup>(17)</sup>; it goes also down very fast in the reaction  $\pi^- + p \rightarrow \eta + n$  <sup>(18)</sup> when the momentum transfer  $-t$  goes beyond  $0.3$  (GeV)<sup>2</sup>.

The following of this section is devoted to a quantitative comparison of the cross-sections for  $\pi$  and  $\eta$  production by pions and photons, as a contribution to the understanding of the  $\eta$ -baryon forces, and their influence in the so-called baryon spectroscopy.

4.2. — Let us start by stressing the following points:

— The data on  $\eta$ -production are up to now too scanty to allow a complete phase-shift analysis, independent from the hints and suggestions coming from the  $\pi\mathcal{N}$  spectroscopy.

<sup>(15)</sup> F. BULOS, R. E. LANOU, A. E. PIFER, A. M. SHAPIRO, M. WIDGOTT, R. PANVINI, A. E. BRENNER, C. A. BORDNER, M. E. LAW, E. E. RONAT, K. STRAUCH, J. J. SZYMANSKI, 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).

<sup>(16)</sup> D. BERLEY, P. L. CONNOLLY, E. L. HART, D. C. RAHM, D. L. STONEHILL, B. THEVENET, W. J. WILLIS and S. S. YAMAMOTO: *Phys. Rev. Lett.*, **15**, 641 (1965); P. L. BASTIEN, J. P. BERGE, O. I. DAHL, M. FERRO-LUZZI, D. H. MILLER, J. J. MURRAY, A. H. ROSENFELD and M. B. WATSON: *Phys. Rev. Lett.*, **8**, 114 (1962).

<sup>(17)</sup> C. BALTAY, N. BARASH, P. FRANZINI, N. GELFAND, L. KIRSCH, G. LÜTJENS, D. MILLER, J. C. SEVERIENS, J. STEINBERGER, T. H. TAN, D. TYCKO, D. ZANELLO, R. GOLDBERG and R. J. PLANO: *Phys. Rev. Lett.*, **15**, 532 (1965); P. ANNINOS, L. GRAY, P. HAGERTY, T. KALOGEROPOULOS, G. PALOMBA, S. ZENONE, R. BIZZARRI, G. CIAPETTI, U. DORE, M. GASPERO, G. GIALANELLA, P. GUIDONI, I. LAAKSO, G. MONETI and G. NATOLI: *Proceedings of the Second Topical Conference on Resonant Particles*, Athens, Ohio, June 1965; See also *Proceedings of the LI Conference of the Italian Physical Society*, Bologna, November 1965.

<sup>(18)</sup> O. GUISAN, J. KIRZ, P. SONDEREGGER, A. V. STIRLING, P. BORGEAUD, C. BRUNETON, P. FALK-VAIRANT, B. AMBLARD, C. CAVERSASIO, J. P. GUILLAUD and M. YVERT: *Phys. Lett.*, **18**, 200 (1965).

— The  $\eta$  has in common with the  $\pi^0$  all the quantum numbers (but isospin and mass), and is in addition assigned to the same octet in  $SU_3$  models (the  $K, \bar{K}, \pi, \eta$  octet<sup>(19)</sup>). This invites to the hypothesis that the  $\eta$ - $\mathcal{N}$  resonances are the same isobaric states of the  $\pi$ - $\mathcal{N}$  resonances with branching ratios which may be estimated through  $SU_3$  and phase space<sup>(20,21)</sup>.

— The  $\pi$ - $\mathcal{N}$  spectroscopy begins to be rather well known in the (0.5 ÷ 1.2) GeV region (from  $\pi$  scattering and  $\pi$  photoproduction data) and is characterized by  $\pi$ - $\mathcal{N}$  resonances.

— The diagrams which contribute to  $\eta$  photoproduction (and probably also to  $\eta$  production from pions at our energies) are essentially of the type given in Fig. 12. They have therefore only nucleons or nucleon isobars as propagators

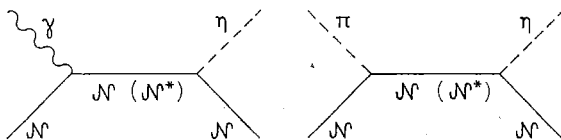


Fig. 12. — Typical graphs contributing to the photoproduction and  $\pi$  production of  $\eta$ 's.  $\mathcal{N}^*$  stands for an isobaric state of the nucleon.

(here and in the following,  $\mathcal{N}$  stands for nucleon,  $\mathcal{N}^*$  for any excited isobaric state).

In this situation, it seems to us a natural starting point to analyse the  $\eta$ -production data in terms of a comparison with  $\pi$ -production data, in order to determine if the  $\eta$ - $\mathcal{N}$  system goes through the same resonances as the  $\pi$ - $\mathcal{N}$  sys-

tem, or if (also) there are peculiar  $\eta$ - $\mathcal{N}$  resonances. We shall see that the second case is probably the right one. The comparison must be done between  $\pi$ - $\mathcal{N}$  and  $\eta$ - $\mathcal{N}$  states with the same isospin and total angular momentum.

To compare the  $\pi$ - $\mathcal{N}$  and the  $\eta$ - $\mathcal{N}$  systems, let us consider the following cross-sections, and the corresponding reactions with a proton in the initial state:

$$(4a) \quad \left( \frac{d\sigma}{d\Omega^*} \right)_{\pi^-\eta}, \quad \pi^- + p \rightarrow \eta + n,$$

$$(4b) \quad \left( \frac{d\sigma}{d\Omega^*} \right)_{\pi^-\pi^0}, \quad \pi^- + p \rightarrow \pi^0 + n,$$

$$(4c) \quad \left( \frac{d\sigma}{d\Omega^*} \right)_{\pi^-\pi^-}, \quad \pi^- + p \rightarrow \pi^- + p,$$

$$(5a) \quad \left( \frac{d\sigma}{d\Omega^*} \right)_{\gamma\eta}, \quad \gamma + p \rightarrow \eta + p,$$

<sup>(19)</sup> M. GELL-MANN: *Phys. Rev.*, **125**, 1067 (1962).

<sup>(20)</sup> A. W. HENDRY and R. G. MOORHOUSE: *Phys. Lett.*, **18**, 171 (1965).

<sup>(21)</sup> R. F. DASHEN: *Nuovo Cimento*, **32**, 469 (1964).

$$(5b) \quad \left( \frac{d\sigma}{d\Omega^*} \right)_{\gamma\pi^0}, \quad \gamma + p \rightarrow \pi^0 + p,$$

$$(5c) \quad \left( \frac{d\sigma}{d\Omega^*} \right)_{\gamma\pi^+}, \quad \gamma + p \rightarrow \pi^+ + n,$$

and the corresponding total cross sections  $\sigma(\pi^-, \eta)$  etc.

We must first separate the different isospin states. Our procedure stays on the following points

The reactions  $(\pi^-, \eta)$ ,  $(\gamma, \eta)$  are pure  $T = \frac{1}{2}$  states.

All the other processes indicated in (4), (5) are mixtures of  $T = \frac{1}{2}$  and  $T = \frac{3}{2}$  isospin states.

It is possible to isolate the  $T = \frac{1}{2}$  isospin in the  $\pi$  scattering: in fact

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

It is not generally possible to isolate the  $T = \frac{1}{2}$  state in  $\pi$  photoproduction, unless we are in a region where  $T = \frac{3}{2}$  is negligible or rather low. This seems to be our case (\*).

With this assumption the relations among the elastic and charge-exchange  $\pi$  cross-sections (4) and the photoproduction cross-sections (5) become rather simple, and with sufficient approximation we assume:

$$(6) \quad \sigma_{\pi\pi}(T = \frac{1}{2}) = \frac{3}{2}[\sigma(\pi^-, \pi^-) + \sigma(\pi^-, \pi^0)]$$

for the scattering, and

$$(7) \quad \sigma_{\gamma\pi}(T = \frac{1}{2}) = \sigma(\gamma, \pi^0) + \sigma(\gamma, \pi^+) \simeq 3\sigma(\gamma, \pi^0)$$

for the photoproduction.

(\*) The assumption that in our energy region ((800-1000) MeV of the incident  $\gamma$ -ray) the states  $T = \frac{3}{2}$  give a small contribution, may be rather well justified:

No resonant state in  $T = \frac{3}{2}$  seems to play an important role between 1400 and 1800 MeV total mass (that is between 600 and 1200 MeV for the incident photon energy).

In our energy region the ratio  $\sigma(\gamma, \pi^+)/\sigma(\gamma, \pi^0)$  is rather close to 2:1, as predicted for  $T = \frac{1}{2}$ .

This ratio is close to 2 at  $180^\circ$  of the  $\pi$ , where the contribution of the direct photoproduction term in the  $\pi^+$  channel is zero. (We thank Prof. C. SCHAEFER for indicating this point on his data).

The cross-section for  $\pi^+$  scattering ( $\pi^+ + p \rightarrow \pi^+ + p$ ) is lower than the corresponding  $\pi^-$  scattering by more than a factor 2<sup>(22)</sup> in the concerned energy region.

<sup>(22)</sup> J. A. HELLAND, C. D. WOOD, T. J. DEVLIN, D. E. HAGGE, M. J. LONGO, B. J. MOYER and V. PEREZ-MENDEZ: *Phys. Rev.*, **134**, B 1079 (1964).

These relations are also valid for the differential cross-sections, which are indicated as

$$(\frac{d\sigma}{d\Omega^*})_{\gamma\pi}^{T=\frac{1}{2}}, \quad (\frac{d\sigma}{d\Omega^*})_{\pi\pi}^{T=\frac{1}{2}} \quad \text{etc.}$$

We make now use of these reactions to compare  $\eta$  processes and pion processes in the same isospin state,  $T = \frac{1}{2}$ . In particular we compare the ratios

$$(8) \quad R_\gamma(\theta) = \frac{(\frac{d\sigma}{d\Omega^*})_{\gamma\pi}^{T=\frac{1}{2}}}{(\frac{d\sigma}{d\Omega^*})_{\gamma\eta}} \simeq 3 \frac{(\frac{d\sigma}{d\Omega^*})_{\gamma\pi^0}}{(\frac{d\sigma}{d\Omega^*})_{\gamma\eta}}$$

and

$$(9) \quad R_\pi(\theta) = \frac{(\frac{d\sigma}{d\Omega^*})_{\pi\pi}^{T=\frac{1}{2}}}{(\frac{d\sigma}{d\Omega^*})_{\pi\eta}} \simeq \frac{3}{2} \frac{(\frac{d\sigma}{d\Omega^*})_{\pi^-\pi^-} + (\frac{d\sigma}{d\Omega^*})_{\pi^-\pi^0}}{(\frac{d\sigma}{d\Omega^*})_{\pi\eta}}.$$

We indicate by  $R_\gamma$  (total) and  $R_\pi$  (total) these ratios when referred to the total cross-sections.

The values of  $R_\gamma$ ,  $R_\pi$  as a function of the energy are given in Fig. 13. We calculated the value of  $R_\gamma(120^\circ)$  using our measurements for the  $\eta$ , and the results of other authors on the  $\pi$  photoproduction<sup>(23)</sup>.  $R_\gamma$  (total) was obtained as  $4\pi R_\gamma(\theta)$ , this hypothesis being supported by the isotropy of reaction (1) at  $\sim 800$  MeV<sup>(12)</sup>.

The values of  $R_\pi(\theta)$  are deduced from the measurements of BULOS *et al.*<sup>(14)</sup> on the  $\eta$ , and of the same authors<sup>(24)</sup> and of HELLAND *et al.*<sup>(22)</sup> on the pion exchange and scattering.

The abscissa in Fig. 13 is linear with the momentum ( $P_\eta^*$ ) of the  $\eta$  in the c.m. system. The angle chosen for  $R_\pi(\theta)$  is an average in the interval  $80^\circ \div 120^\circ$  of the  $\eta$  and the  $\pi$  in the c.m.s. The value  $R_\pi$  (total) is less meaningful, due to the very large contribution of the forward scattering in  $(\pi^-, \pi^-)$  and  $(\pi^-, \pi^0)$  processes. This large contribution is probably due to the inelastic processes which reflect themselves in the elastic channel as diffraction scattering<sup>(22)</sup>. Anyway,  $R_\pi$ (total) is reported in Fig. 13, and exhibits the same qualitative behaviour than all the other  $R$  values shown there.

The  $R$  values allow a first quantitative comparison between the  $\pi\mathcal{N}$  and  $\eta\mathcal{N}$  final states. We remark:

<sup>(23)</sup> R. DIEBOLD: *Phys. Rev.*, **130**, 2089 (1963).

<sup>(24)</sup> F. BULOS, R. E. LANOU, A. E. PIFER, A. M. SHAPIRO, M. WIDGOFF, R. PANVINI, A. E. BRENNER, C. A. BORBNER, M. E. LAW, E. E. RONAT, K. STRAUCH, J. J. SZYMANSKI, P. BASTIEN, B. B. BRADSON, 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**, 558 (1964).

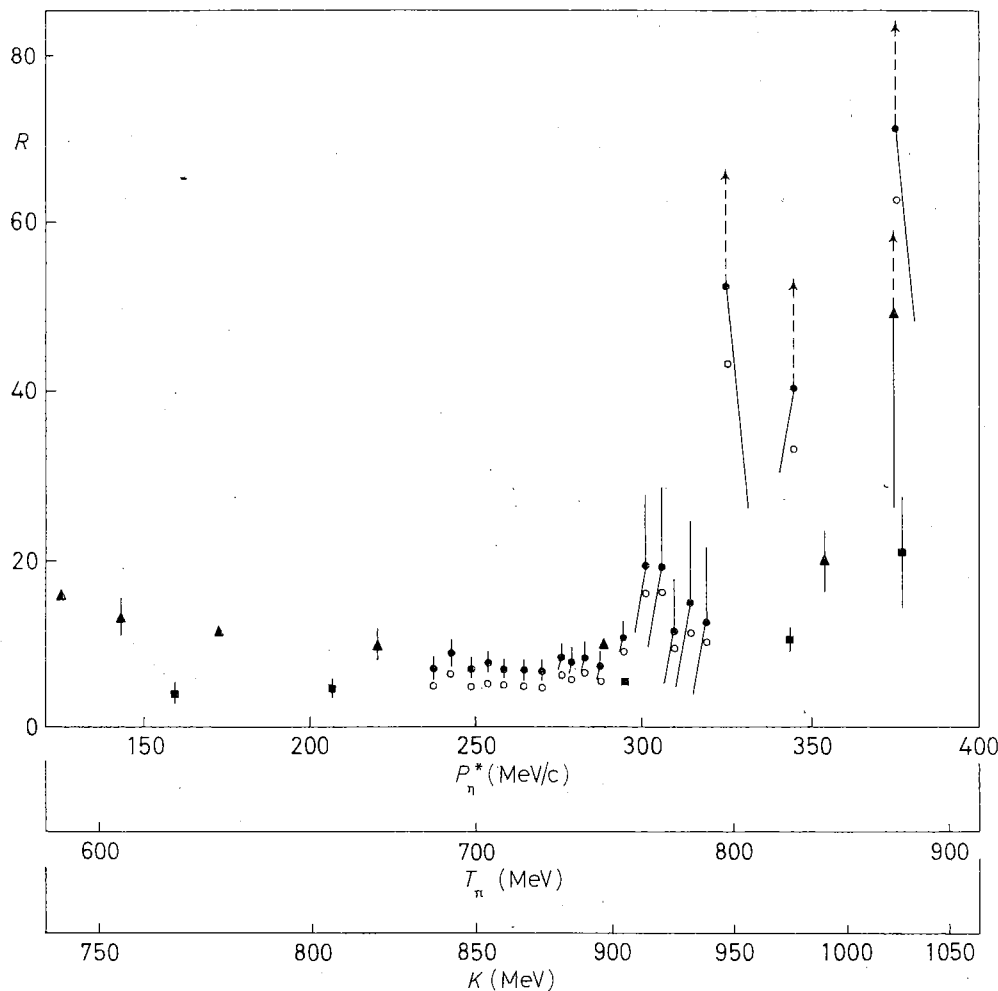


Fig. 13. — The ratio of the  $\pi^-$  to  $\eta$ -production cross-sections, as a function of the c.m. momentum ( $P_\eta^*$ ) of the  $\eta$  (upper scale). The laboratory energy of the particle producing the reaction is also reported in the lower scales: kinetic energy of the pion ( $T_\pi$ ) and photon energy ( $K$ ).  $R_\gamma$  and  $R_\pi$  are defined in the text.  $\bullet$   $R_\gamma(\theta)$ ,  $\theta = 120^\circ$  (Frascati, DIEBOLD (23));  $\circ$   $R_\gamma$  (total) (Frascati, DIEBOLD (23));  $\blacksquare$   $R_\pi(\theta)$ ,  $80^\circ < \theta < 120^\circ$  (HELLAND *et al.* (22), BULOS *et al.* (24));  $\blacktriangle$   $R_\pi$  (total).

a) in the region  $140 \leq P_\eta^* \leq 300$  MeV/c the values of  $R_\gamma$  and  $R_\pi$  are rather low, constant, and close in absolute value. This means that the  $\eta$  is rather abundant in this energy interval (one  $\eta$  every 4 or 5 pions); in addition, being  $R_\gamma(\theta)$  so close to  $R_\pi(\theta)$ , the isospin formalism we followed to extract the  $T = \frac{1}{2}$  state gives results which are remarkably consistent with the experimental evidence.

b) As we go beyond 300 MeV/c of  $P_\eta^*$ , the ratios  $R$  increase rapidly to show that pions (from the elastic channels and from single photoproduction) become relatively more abundant with respect to  $\eta$ 's.

From these results we could be, at first sight, led to conclude that the  $\eta$  shares with the pions the second resonance:  $N^{* *}$  (1512 MeV),  $D_{\frac{1}{2}, \frac{3}{2}}$ .

However, following an argument by DASHEN<sup>(21)</sup>, the angular momentum factors alone would reduce the contribution of  $\mathcal{N}^{**}(1512)$  in the  $\eta$  production by a factor larger than 200 as compared to the  $\pi$  production. This is very low as compared with the experimental values of  $R$  we gave in Fig. 13, unless we assume unreasonably high values for the  $\eta$ - $\mathcal{N}$ - $\mathcal{N}^{**}$  coupling. If any, there is some evidence that the couplind  $G(\eta\mathcal{N}\mathcal{N}^{**}) \simeq 0.2G(\pi\mathcal{N}\mathcal{N}^{**})$ <sup>(21,25)</sup>. Thus, it is very improbable that the relatively high value of the  $\eta$  photoproduction cross-section at (750÷850) MeV of the incident photon, can be due to the second resonance (\*).

4.3. - The high value of  $(d\sigma/d\Omega^*)_{\gamma\eta}$  at our lowest energies and its fast decrease after 900 MeV (Fig. 11) suggest therefore the hypothesis that there is in the  $\eta$ - $\mathcal{N}$  system a resonance or an important state which is not so relevant in the  $\pi$ - $\mathcal{N}$  system.

This conclusion is not new. In fact the idea that the behaviour of the  $\eta$  production near threshold is not due to the second resonance, but is rather indicative of an  $S$ -wave resonance in the  $\eta$ -baryon system has already been considered by GYUK and TUAN<sup>(27)</sup>. More recently HENDRY and MOORHOUSE<sup>(10)</sup> have examined the situation after the measurements of BULOS *et al.*<sup>(15)</sup> and PAULI *et al.*<sup>(28)</sup> on the channels

$$(10) \quad \pi^- + p \rightarrow \eta + n$$

and

$$(11) \quad \pi^+ + n \rightarrow \eta + p$$

They conclude that the sharp linear rise of the cross-section as observed in reaction (10), as well as the isotropic c.m. angular distribution up to 800 MeV K.E. of the pion, strongly suggest that the production occurs predominantly in an  $S$ -state.

<sup>(25)</sup> S. L. GLASHOW and A. H. ROSENFELD: *Phys. Rev. Lett.*, **10**, 192 (1963); See also ref. <sup>(21)</sup>.

(\*) Another argument to exclude the second resonance is in the fact that  $(d\sigma/d\Omega^*)_{\gamma\eta}$  as well as  $(d\sigma/d\Omega^*)_{\pi\eta}$  are close to isotropy<sup>(12,15)</sup>. A consistent attempt to reconcile isotropy with a dominant  $D_{\frac{1}{2},\frac{3}{2}}$  state has been done by ALTARELLI *et al.*<sup>(26)</sup>, when the photoproduction isotropy was still unknown, by interference with an  $S$ -wave. It is improbable that the  $D$ - $S$  interference works towards isotropy at the same time in the photon and pion input channels.

<sup>(26)</sup> G. ALTARELLI, F. BUCCELLA and R. GATTO: *Nuovo Cimento*, **35**, 331 (1965).

<sup>(27)</sup> I. P. GYUK and S. F. TUAN: *Phys. Rev. Lett.*, **14**, 121 (1965).

<sup>(28)</sup> E. PAULI, A. MULLER, R. BARLOUTAUD, L. CARDIN, J. MEYER, M. BENEVENTANO, G. GIALANELLA, L. PAOLUZI and R. FINZI: *Proceedings of the Sienna International Conference on Elementary Particles*, vol. I (September 1963), p. 92.

More precisely, the cross-section goes approximately linear with the  $\eta$  center-of-mass momentum, according to the formula for  $S$ -wave production

$$(12) \quad \sigma(\pi + \mathcal{N} \rightarrow \eta + \mathcal{N}) \propto \left(\frac{k_2}{k_1}\right) |T_{12}|^2,$$

where we indicate by 1, 2 the two channels  $\pi + \mathcal{N}$  and  $\eta + \mathcal{N}$  respectively;  $k_1$  ( $k_2$ ) is the c.m. momentum in channel 1 (2);  $T_{12}$  is the transition matrix element.

To fix the character of this  $S$ -state interaction (that is to look for a resonant behaviour) it is important to examine the development of the cross-section values after the rise. HENDRY and MOORHOUSE<sup>(20)</sup> find that the decrease at higher energies is rather sharp, and seems to require a strong energy variation in the  $T$ -matrix element. A strong energy variation has likewise been observed in phase shift analysis of  $\pi$ - $\mathcal{N}$  scattering for the  $S_{\frac{1}{2},\frac{1}{2}}$  partial wave at energies near the  $\eta$  threshold<sup>(29-31)</sup>, the behaviour being strongly suggestive of an  $S$ -wave resonance in the inelastic channels.

On these suggestions, HENDRY and MOORHOUSE<sup>(20)</sup> went to a quantitative analysis of channels 1 and 2. They used a multichannel effective range formalism<sup>(32)</sup> and arrived to the following conclusions:

- There is a good correspondence in energy position between the  $S_{\frac{1}{2},\frac{1}{2}}$  inelastic pion collision nucleon (identified by the absorption parameter and its phase shift) and the  $\eta$  production. Notwithstanding, the  $\eta$  production does not fully account for the value of the absorption parameter: a background from one or more channels seems to be necessary.
- When some space is left to the « background » then all the numerical computations tend to individuate the  $S$ -state in  $\eta$  production as an  $S_{\frac{1}{2},\frac{1}{2}}$  resonance with the following characteristics:

$$(13) \quad E_r = 1519; 1505 \text{ MeV}, \quad \Gamma = 130; 77 \text{ MeV}.$$

$E_r$  is the effective mass of the  $\eta$ - $\mathcal{N}$  resonance, while  $\Gamma$  is its full width. The first values in  $E_r$  and  $\Gamma$  come from using the evaluations of BRANSDEN *et al.*<sup>(29)</sup> and the second values from AUVIL *et al.*<sup>(30)</sup>.

<sup>(29)</sup> B. H. BRANSDEN, P. J. O'DONNELL and R. G. MOORHOUSE: *Phys. Lett.*, **11**, 339 (1964); Rutherford Lab. Report NIRL/R/79.

<sup>(30)</sup> P. AUVIL, C. LOVELACE, A. DONNACHIE and A. T. LEA: *Phys. Lett.*, **12**, 76 (1964).

<sup>(31)</sup> L. D. ROPER: *Phys. Rev. Lett.*, **12**, 340 (1964); L. D. ROPER and R. M. WRIGHT: UCRL 7846 (1964).

<sup>(32)</sup> M. H. ROSS and G. L. SHAW: *Ann. of Phys.*, **9**, 391 (1960); **13**, 147 (1961); R. H. DALITZ: *Ann. Rev. Nucl. Sci.*, **13**, 339 (1963).



Now we go back to our results for photoproduction. It is interesting to note that the decrease of the photoproduction cross-section with the energy is faster than in the reaction (10), where the  $\eta$ 's come from pion beams.

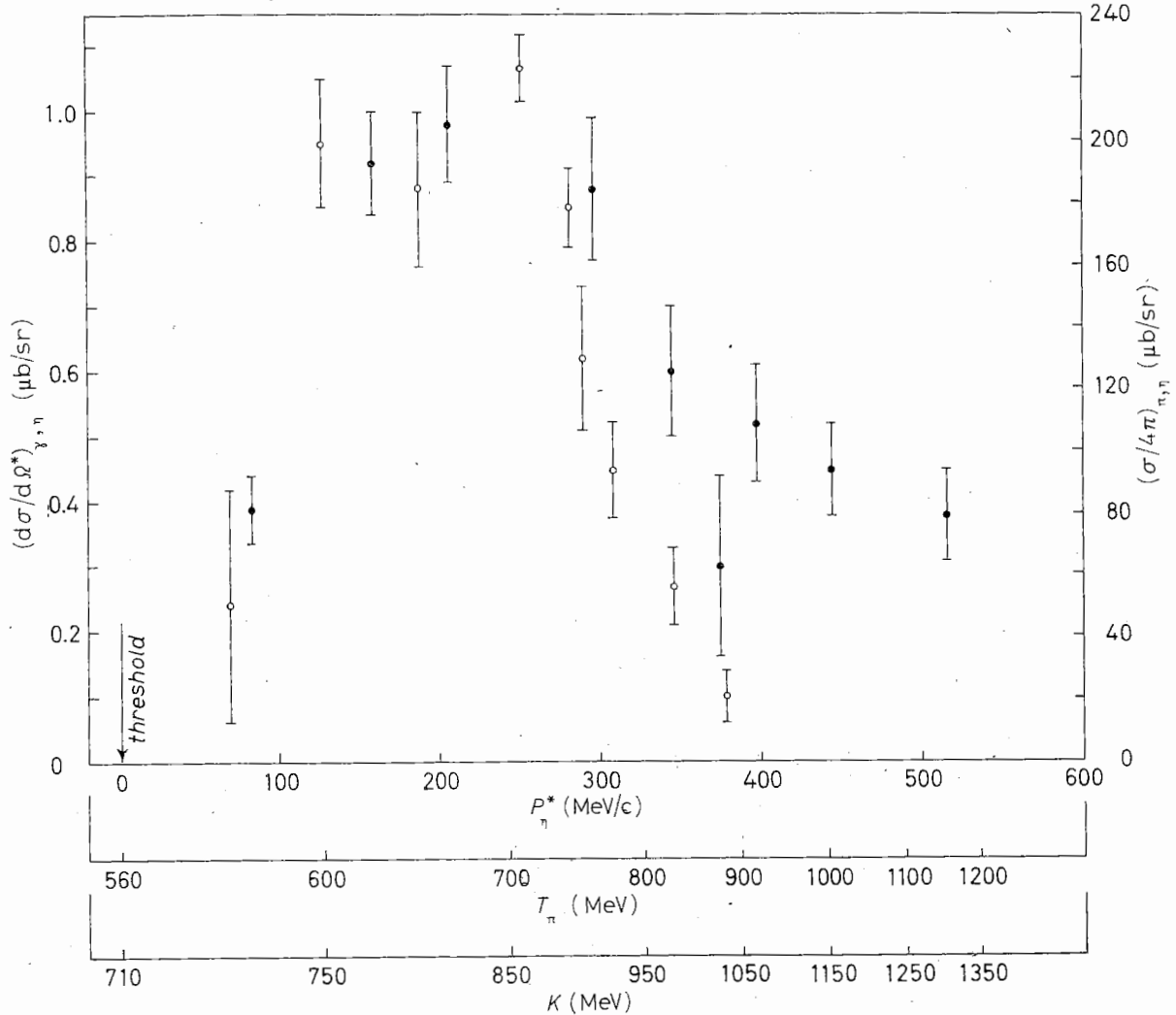


Fig. 14. — Comparison between the cross-section of  $\eta$  photoproduction and  $\eta$  production by pions<sup>(15)</sup>. The abscissa is linear in the  $\eta$  c.m. momentum  $P_\eta^*$  (upper scale). In the lower scales the energy ( $K$ ) of the incident photon and the kinetic energy ( $T_\pi$ ) of the incident pion in the laboratory system, are reported. The photoproduction data are to be referred to the left ordinate scale and the  $\pi$  production data to the right ordinate scale. The photoproduction data are an average of the present results and the results of ref. (13). To get the cross-section for  $\eta$  production from our results and from the results on  $\eta$  production by pions, the measured cross-section referring to the decay mode  $\eta \rightarrow \gamma\gamma$  was divided by the branching ratio  $(\eta \rightarrow \gamma\gamma)/(\eta \rightarrow \text{all modes}) = 0.38$  (14). To give better statistical significance to the comparison we report  $\sigma/4\pi$  instead of  $d\sigma/d\Omega^*$  for the data on reaction  $\pi^- + p \rightarrow \eta + n$ :  $d\sigma/d\Omega^*$  at our angles has the same behaviour as  $\sigma/4\pi$ , with much larger errors. •  $\pi^- + p \rightarrow \eta + n$ , o  $\gamma + p \rightarrow \eta + p$ .

This can be seen in Fig. 14, where we report both photoproduction cross-section and the cross-section of reaction (10).

The fast decrease of the photoproduction cross section (Fig. 11) supports the resonance hypothesis with even more immediate evidence than in reaction (10), considering also that, as we said, we already know <sup>(12)</sup> that the  $\eta$  photoproduction near threshold is rising at least as fast as the  $\eta$  production by pions, and also has an isotropic angular distribution.

It is not possible to make in photoproduction an analysis of the type that HENDRY and MOORHOUSE <sup>(20)</sup> made using the pion channel, for lack of equivalent information in pion photoproduction. If we try to judge the width of this resonance from the behaviour of the cross-section in Fig. 11, we find that the possible width of the  $S_{\frac{1}{2},\frac{1}{2}}$  resonance is around 150 MeV: a value in agreement with the estimation of HENDRY and MOORHOUSE <sup>(20)</sup>.

4.4. — Let's go now to consider the values of  $(d\sigma/d\Omega^*)_{\gamma\eta}$  at energies higher than 940 MeV. We have at disposal the points up to 1030 MeV, obtained in this experiment and in the previous work of our group <sup>(2,33)</sup>. As we said, the cross-section for  $\eta$  photoproduction decreases by a factor  $\sim 5 \div 10$  with respect to the value at 830 MeV (Fig. 11), and the values of  $R$  increase (Fig. 13).

It is difficult to assume that this « residual » cross-section is a tail of the  $S_{\frac{1}{2},\frac{1}{2}}$  resonance, also considering that in reaction (10) the  $\eta$  cross-section is not isotropic at the highest energies, that is beyond  $\sim 800$  MeV for the pion kinetic energy.

Again, the world information in photo- and pion-production of the  $\eta$  is not enough to try any wave analysis: but this is the region of the well-known third resonance (1688 MeV,  $F_{\frac{1}{2},\frac{3}{2}}$ ; indicated in the following by  $\mathcal{N}^{***}$ ) and one can compare, as before for the second resonance, the values of  $(d\sigma/d\Omega^*)_{\gamma\eta}$  and  $(d\sigma/d\Omega^*)_{\gamma\pi}$  to see if the production around 1000 MeV of the incident photon could be due to the third resonance.

Following DASHEN <sup>(21)</sup> again, when assuming that the cross-sections are completely dominated by the third resonance, one finds

$$(14) \quad \frac{(d\sigma/d\Omega^*)_{\gamma\eta}}{(d\sigma/d\Omega^*)_{\gamma\pi^0}} = \frac{G^2(\eta\mathcal{N}\mathcal{N}^{***})}{G^2(\pi\mathcal{N}\mathcal{N}^{***})} \cdot \frac{f(q_\eta)}{f(q_\pi)},$$

where  $G(\eta\mathcal{N}\mathcal{N}^{***})$  and  $G(\pi\mathcal{N}\mathcal{N}^{***})$  are the coupling constants of the  $\eta$  and the  $\pi$  respectively, with  $\mathcal{N}$  and  $\mathcal{N}^{***}$ ;  $f(q)$  is a kinematical factor which includes the effects of phase space and angular momentum barrier. One can reasonably estimate  $f(q_\eta)/f(q_\pi) \simeq \frac{1}{3}$ . The ratio of the coupling constants is unknown: if  $\mathcal{N}^{***}$

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<sup>(33)</sup> C. BACCI, G. PENSO, G. SALVINI, A. WATTENBERG, C. MENCUCINI, R. QUERZOLI and V. SILVESTRINI: *Proceedings of the Conference on Photon Interactions in the GeV-Energy Range*, (Cambridge, Mass., Jan. 1963), p. IV, 6.

belongs to an octet representation of  $SU_3$ , we have <sup>(19,21)</sup>

$$(15) \quad G(\eta \mathcal{N} \mathcal{N}^{***}) \simeq \frac{1}{\sqrt{3}} (3 - 4\alpha) G(\pi \mathcal{N} \mathcal{N}^{***}),$$

where  $\alpha$  is the ratio of  $D$  to  $F$ -type couplings.

Relation (14), when the value  $\frac{1}{3}$  for  $f(q_\eta)/f(q_\pi)$  is taken, and the ratio of the cross-sections is taken from Fig. 13, at  $K = 980$  MeV, becomes

$$(16) \quad \frac{G^2(\eta \mathcal{N} \mathcal{N}^{***})}{G^2(\pi \mathcal{N} \mathcal{N}^{***})} \leq 3 \frac{(d\sigma/d\Omega^*)_{\gamma\eta}}{(d\sigma/d\Omega^*)_{\gamma\pi^0}} \simeq 0.15.$$

The equality holds in the hypothesis that all the  $\eta$  cross-section at (950–1000) MeV is due to the  $\mathcal{N}^{***}$  resonance.

The ratio (16) corresponds, according to (15), to a value of  $\alpha \simeq 0.58$ , to be compared with the value  $\alpha = 0.66$  which is generally accepted <sup>(29)</sup>, according to  $SU_6$ . This cannot be considered a significant agreement; in fact we are in a critical region: the ratio

$$\frac{G^2(\eta \mathcal{N} \mathcal{N}^{***})}{G^2(\pi \mathcal{N} \mathcal{N}^{***})}$$

becomes 0.037 instead of 0.15 for  $\alpha = \frac{2}{3}$ .

In conclusion, there is enough  $\eta$  production around 1000 MeV to leave just the possible foreseen space to the third resonance. On the other side the energy distributions of reactions (1) and (10) as well as the dependence of  $R$  on energy (see for instance  $R_\pi$  (total) in Fig. 13) do not indicate any bump or maximum of the cross-section in the region of the third resonance.

## 5. – Conclusions.

Our results on the photoproduction cross-section of the  $\eta$  in the process  $\gamma + p \rightarrow \eta + p$ , which are summarized in Fig. 11 and in Tables II, III allow the following conclusions:

- The  $\eta$  is produced with high abundance at the lowest energies ((830–900) MeV of the incident  $\gamma$ ), and its cross-section has a fast descent in the (900–1000) MeV interval.
- The absolute value of the cross-section for photoproduction, and even more clearly the comparison with the photoproduction of the pions, excludes that around 800 MeV the  $\eta$  can be produced through the  $\eta$ - $\mathcal{N}$  decay of the second  $\pi$ - $\mathcal{N}$  resonance.

- The energy dependence of the cross-section from 800 to 1000 MeV of the incident  $\gamma$ , gives instead good support to the hypothesis, already presented on the basis of the results on reactions  $\pi + \mathcal{N} \rightarrow \eta + \mathcal{N}$ , that the  $\eta$  is produced near threshold in a  $S_{\frac{1}{2}, \frac{1}{2}}$   $\eta$ -nucleon resonance, with  $E_r \simeq 1520$  MeV, and  $\Gamma \simeq 150$  MeV.
- We find a remarkable consistency between the input channels  $\pi^- + p$  and  $\gamma + p$  at the energies considered here, when the  $T = \frac{1}{2}$  state is extracted from both channels. In fact the ratios  $R_\gamma$  and  $R_\pi$  (Fig. 13) have the same energy dependence, and their absolute values are about equal at each energy. The results agree with the assumption that the reactions (5b) and (5c) are dominated by a  $T = \frac{1}{2}$  isotopic-spin state.
- The photoproduction at (950–1050) MeV could be due (or not) to the third resonance: in fact the value of the cross-section at those energies does not disagree with possible  $SU_3$  previsions. It is clear anyway that the majority of the  $\eta$  production which is below 900 MeV of the incident photon energy does not follow the known  $\pi$ - $\mathcal{N}$  resonances.

## RIASSUNTO

Abbiamo misurato, sull'Elettrosincrotrone di Frascati da 1.1 GeV, la sezione d'urto per fotoproduzione di  $\eta$  per energie  $K$  del fotone incidente comprese fra  $\sim 800$  e  $\sim 1000$  MeV. La sezione d'urto differenziale per questo processo, ad un angolo dell' $\eta$  nel c.m. di  $\sim 110^\circ$ , risulta pressoché costante per  $830 \text{ MeV} \leq K \leq 900 \text{ MeV}$ , per crollare di un fattore  $5 \div 10$  a  $K = 950 \text{ MeV}$ . Questi risultati vengono discussi attraverso un confronto con i dati sulla produzione di  $\eta$  da pioni, e con i dati sulla diffusione pione-nucleone e sulla fotoproduzione di pioni. Le conclusioni sono in accordo con l'ipotesi che il sistema  $\eta$ - $\mathcal{N}$  sia dominato a basse energie da una risonanza con momento angolare orbitale  $l = 0$  (risonanza  $S_{\frac{1}{2}, \frac{1}{2}}$ ).