C. Bacci, G. Penso, G. Salvini, C. Mencuccini and V. Silvestrini :
PHOTOPRODUCTION OF THE η -PARTICLE.

D-wave angular momentum barrier for π° versus η° production, and assuming that the η°-nucleon and π°-nucleon couplings are approximately equal.

3. The angular distribution near threshold, although only containing 4 points also tends to rule out pure D-wave production of the η° since this requires $2 + 3 \sin^2 \theta^*$ for the angular distribution; a ratio of $5/2$ for 0° or 180° versus 90°. Our results are consistent with an isotropic angular distribution.

4. This suggests $s_{\frac{1}{2}}$ and/or $p_{\frac{1}{2}}$ production for the η° near threshold. The $p_{\frac{1}{2}}$, $T = \frac{1}{2}$ phase shift in pion-nucleon scattering which is now known to go through 90° (or come very close to 90°) at a CM energy of ~ 1490 MeV may play a role in η° photoproduction near threshold.

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Photoproduction of the η-Particle

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The photoproduction of the eta particle in the process

$$\gamma + P \rightarrow \eta + P \tag{1}$$

is under study at Frascati, with the 1100 MeV electron-synchrotron, in the energy region 750–1000 MeV of the incident gamma.

The cross section of the process (1) is being measured at different energies. The preliminary results at 100–120° c. m. are reported in this paper.

In section 1 we give some reasons of interest of our measurements; in section 2 the experimental disposition; in section 3 our present results; in section 4 the discussion and the comparison with the charge exchange production of the η.

§ 1. – The reasons of interest of our measurements

In addition to the obvious general interest in the production cross section of the η and its anomalies, it is possible to give some valid specific reasons of interest, which we briefly resume here.

The spin and parity of the η is the same as for the pion's. It is therefore significant to compare at least the reactions:

$$\gamma + p \rightarrow \pi^\circ + p \qquad (2)$$

$$\pi^- + p \rightarrow \pi^\circ + n \qquad (3)$$

$$K^- + p \rightarrow \pi^\circ + \Lambda \qquad (4)$$

with the corresponding reactions of the eta:

$$\gamma + p \rightarrow \eta + p \qquad (5)$$

$$\pi^- + p \rightarrow \eta + n \qquad (6)$$

$$K^- + p \rightarrow \eta + \Lambda \qquad (7)$$

in order to see, when the kinematics allows the comparison:

a) if the eta is produced through the same nucleon resonances (isobaric states) or at least the same orbital momenta than the π°.

b) which is the behaviour of the eta cross section close to the threshold.

More specifically, the interest of the points a) and b) is stimulated from the rather precise position of the eta in the SU3 and more recently in the SU6 system. A preliminary study of the situation has been done by Fujii and Holloway [1], and by Dashen [2]. At least in some cases, the ratio among the coupling constants in the baryons – π° vertex and the baryons – η vertex can be foreseen, and compared with the experiment.

Whatever model or theory one chooses, one must succeed to fix the angular momenta of the final η-nucleon system, going through a phase analysis of the reactions (5),(6).

Some experimental results have already been obtained, on the total cross section and the angular distribution. Photoproduction of the eta in reaction (1) has been demonstrated and measured at two energies around 100° c.m. in our previous work [3]. The reaction (6) has been studied more extensively [4].

In processes (6) (as well as in (7)) the η production has a fast rather linear rise, which already gets its maximum around 650 MeV of the π^- in the lab, and the angular distribution agrees with isotropy. The models proposed until now consider the states $P_{1/2}, D_{3/2}, S_{1/2}$ for the final state of the η-p system [5,6], the $D_{3/2}$ being the so called second resonance.

Our present contribution extends the information on the photoproduction of the η particle. It is the first part of a larger program aiming to separate the states involved in the η photoproduction, by measuring at different angles (60–120°). It is interesting to note the complementarity of the channels (5), (6), which for instance could greatly differ on the S wave.

§ 2. – Experimental disposition and method

The experimental disposition is given in Fig. 1.

The γ ray beam from the electronsynchrotron hits the 7.4 cm H_2 target. The protons are measured in the telescope P, which is a combination of counters and four spark chambers.

On the line of flight of the η there is a γ ray detector. It is the total absorp-
tion, lead glass Cerenkov counter C, with an anticoincidence counter in front
S_5. The energy of the γ ray detected by C is measured by a pulse height
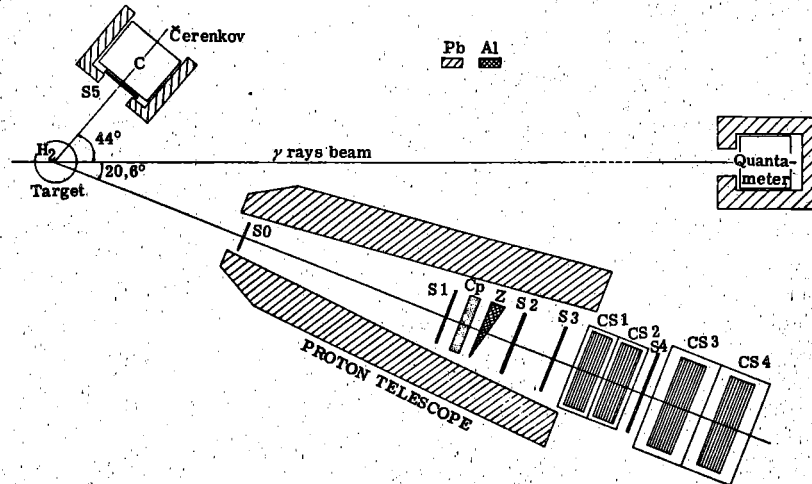analyzer and recorded on the photograph of the spark chambers.

Fig. 1. Experimental disposition. The telescope detectes the protons, whose range is
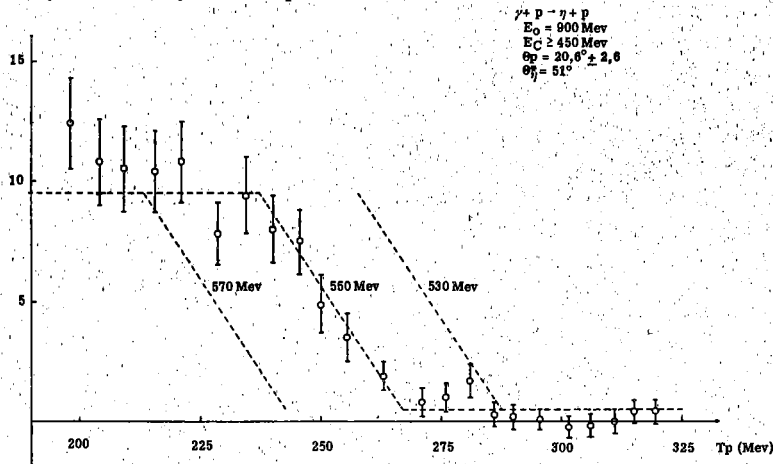carefully measured by the four spark chambers

Fig. 2. The step of the η in the energy distribution of the protons. The dotted lines
indicate our mass resolution, which appears rather good. The mass of the η is known
to be 548 MeV. E_0 is the energy of the electronsynchrotron. C_2 455 MeV indicates
that the points refer to events with a decay photon from the η with an energy greater
than 450 MeV

The η is detected by two different methods, which already were described by
us [3]. One is based on the analysis of the γ ray pulses in C (γ ray method);
the other (see Fig. 2) on the energy distribution of the protons in the proton

channel (step method). An alternative way of the step method (differentiation method) consists in plotting (see for instance Fig. 3) the energy distribution of the protons for a "monochromatic" incident γ ray beam at a given angle in the laboratory. This is simply obtained by taking the difference between the results at two different energies K_1, K_2 of the electronsynchrotron.
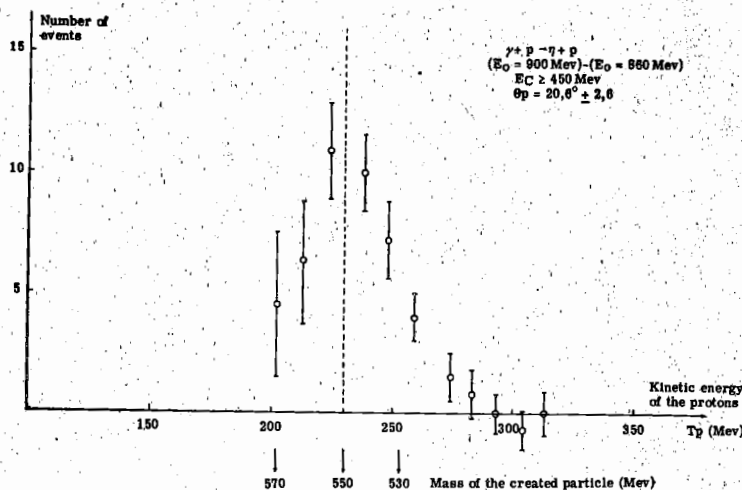

Fig. 3. An example of our subtraction method

This is the more direct evidence of the existence of process (1). In Fig. 3 the difference is reported between 900 and 800 MeV of the incident γ ray beam at a laboratory angle of $20.6° \pm 2.35°$ of the recoil proton. The η must manifest itself as a peak corresponding to a "missing mass" of 548 MeV, with an experimental width determined by the width of the bremsstrahlung step, by our energy resolution, and by the value of $k = k_2 - k_1$.

In Fig. 3 we report in abscissas the expected position of the peak for different masses of the "η".

§ 3. – Results

In Table 1 and in Fig. 4 we report our present results, that is the cross section in the interval 100–120°c.m. for different energies of the incident γ, for the process (1). The results have been obtained by using the "step method" and the "differentiation method".

The c.m. cross sections $(d\sigma/d\Omega)_{\gamma\gamma}$ in col. 2, and reported in Fig. 4, are relative to the decay mode $\eta \rightarrow \gamma\gamma$ of the eta. In fact they have been calculated taking the events with an high pulse ($E_c \geq 450$ MeV) in the Cerenkov C, so that only the $\gamma\gamma$ mode is practically observed. The differential cross section relative to all the decay modes of the eta may be obtained by assuming $\Gamma_{\gamma\gamma}/\Gamma_{total} \sim 0.33$ [3].

Table 1. Differential cross sections for the process $\gamma + p \to \eta + p$.
Col. 1 energy of the incident γ ray, laboratory system. Col. 2 cross section in the c.m., relative to the η decaying in the mode $\eta \to \gamma + \gamma$. Col. 3 an estimate of the differential cross section of the eta, all modes.
The absolute values still have a $\pm$ 30 % uncertainty (see text).

(1) K (MeV)	(2) $(d\sigma/d\Omega)_{\gamma\gamma}$ $(10^{-31} cm^2/sr)$	(3) $(d\sigma/d\Omega)$ $(\mu barn/sr)$
836	5.0 ± 0.6	1.43 ± 0.15
841	3.9 ± 0.6	1.26 ± 0.14
847	4.8 ± 0.7	1.47 ± 0.15
853	4.4 ± 0.7	1.48 ± 0.15
859	4.8 ± 0.7	1.68 ± 0.15
866	4.9 ± 0.6	1.55 ± 0.15
873	4.8 ± 0.7	1.46 ± 0.15
879	3.6 ± 0.7	1.13 ± 0.13
884	4.0 ± 0.9	1.27 ± 0.3
889	3.6 ± 0.9	1.16 ± 0.3
895	4.1 ± 0.9	1.24 ± 0.3
905	2.8 ± 0.5	0.82 ± 0.15
915	1.6 ± 0.7	0.49 ± 0.15
921	1.6 ± 0.8	0.69 ± 0.3
926	2.4 ± 1.4	0.66 ± 0.4
932	2.1 ± 1.4	0.59 ± 0.3
937	2.3 ± 1.5	0.55 ± 0.3
944	0.7 ± 0.9	0.39 ± 0.2
950	0.3 ± 1.0	0.65 ± 0.4
955	0.6 ± 1.1	0.45 ± 0.3

In the column (3) of Table 1 we have reported an estimate of the cross section $(d\sigma/d\Omega)$ of process (1), relative to all the decay modes. These values have been obtained taking into account all the events in C_2 beyond 320 MeV, and assuming the branching ratios:

$$(3\pi^0 + \pi^0 \gamma\gamma) = 33\%$$

$$(\gamma\gamma) = 33\%$$

$$(\pi^+ \pi^- \pi^0) = 27\%$$

$$(\pi^+ \pi^- \gamma) = 7\%$$

The comparison between the π's and η's relative abundances has been made by use of the data of column 3.

The errors in col. (2), (3) include the errors in the background subtraction. In addition, being still in progress the absolute calibration of some elements (e.g. the Cerenkov C), the absolute value of the cross sections in col. (2) and (3) and in Fig. 4 may still be uncertain by a common factor $1 \pm .25$.
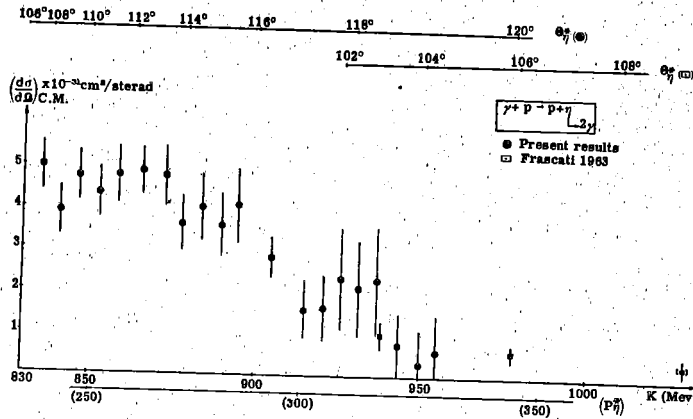

Fig. 4. Present results $d\sigma/d\Omega$ as a function of energy. The angle of the emitted η in the C.m. is indicated in the lines parallel to the abscissas

We make the following comments:

1. As shown in Fig. 4, the cross section for η photoproduction goes down quite fast with the energy, in the interval 830–1000 MeV.

2. This decrease is analogous to the behaviour of the η production cross section in the channel $\pi^- + p \to \eta + n$ [4].

3. This decrease of the η is in contrast with the increase in the cross section of the π's (scattering and photoproduction) in the region of the so called IIIrd resonance (890 ± 80 MeV, pion kinetic energy).

§ 4. – Comparison of the η and the π cross sections

A good point of reference in evaluating the behaviour of the η is to compare the following cross sections on protons:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\pi^-,\eta}; \qquad \left(\frac{d\sigma}{d\Omega}\right)_{\pi^-,\pi^\circ}; \qquad \left(\frac{d\sigma}{d\Omega}\right)_{\pi^-,\pi^-} \qquad (8)$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{\gamma,\eta}; \qquad \left(\frac{d\sigma}{d\Omega}\right)_{\gamma,\pi^\circ}; \qquad \left(\frac{d\sigma}{d\Omega}\right)_{\gamma,\pi^-} \qquad (9)$$

and the corresponding total cross sections. (π^-, η) stands for $\pi^- + p \to n + \eta$; (γ, π°) for $\gamma + p \to p + \pi^\circ$ etc.

In order to make the comparison and the ratio π/η in photoproduction and scattering as meaningful as possible, we must individuate well defined isotopic spin states. Our procedure is briefly given in the following.

11*

One keeps in mind:

1. (π, η), (γ, η) are $T = \frac{1}{2}$ isotopic spin states.

2. All the other processes indicated in (8), (9) are a mixture of $T = \frac{1}{2}$ and $T = \frac{3}{2}$ isospin states.

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

$$\sigma_\pi(T = \tfrac{1}{2}) = \tfrac{3}{2}\left[\sigma(\pi-, \pi-) + \sigma(\pi-, \pi^\circ) - \tfrac{1}{3}\sigma(\pi+, \pi+)\right]$$

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

In this case the relations among the cross sections (8) and (9) become very simple and precisely:

$$\sigma_\pi(T = 1/2) = 3/2\left(\sigma(\pi-, \pi-) + \sigma(\pi-, \pi^\circ)\right) \tag{10}$$

for the scattering

$$\sigma_\gamma(T = 1/2) = \sigma(\gamma\pi^\circ) + \sigma(\gamma, \pi^+); \qquad \frac{\sigma(\gamma\pi^+)}{\sigma(\gamma\pi^\circ)} \approx 2 \tag{11}$$

for the photoproduction.

These relations are also valid for the differential cross sections.

We make therefore use of (10), (11) to compare pion processes and η processes in the same state $T = \frac{1}{2}$. In particular we measure and compare the ratios:

$$R_\gamma(\theta) = \frac{(d\sigma/d\Omega)_{\gamma, T=1/2}}{(d\sigma/d\Omega)_{\gamma\eta}} = \frac{(d\sigma/d\Omega)_{\gamma\pi^\circ} + (d\sigma/d\Omega)_{\gamma\pi^+}}{(d\sigma/d\Omega)_{\gamma\eta}} \cong \frac{3(d\sigma/d\Omega)_{\gamma,\pi^\circ}}{(d\sigma/d\Omega)_{\gamma,\eta}} \tag{12}$$

and

$$R_\pi(\theta) = \frac{(d\sigma/d\Omega)_{\pi, T=1/2}}{(d\sigma/d\Omega)_{\pi,\eta}} = \frac{3/2\left[(d\sigma/d\Omega)_{\pi-,\pi-} + (d\sigma/d\Omega)_{\pi-,\pi^\circ}\right]}{(d\sigma/d\Omega)_{\pi,\eta}} \tag{13}$$

We indicate by $R(tot)$ the ratios referred to the total cross sections.

The values of R_γ, R_π are given in Fig. 5, and make more precise the qualitative considerations expressed at the end of § 3. We have calculated the value of $R_\gamma(120^\circ)$ using our measurements for the η and the results of other authors on the π° [7] photoproduction. R_γ (total) is a pure speculation based on the guess (still to be proved in our measurements) that the photoproduction of the η is isotropic.

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[1] The assumption that in our energy region (800–1000 MeV of the incident γ ray) the state $T = \frac{3}{2}$ may be neglected rests on the following points:

1. No $T = \frac{3}{2}$ state, resonant or not, has been observed between 1400 and 1800 MeV total mass (that is between ~ 600 and 1200 MeV of the γ rays, or more) [10].

2. In our energy region the ratio $\sigma(n, \pi+)/\sigma(p, \pi^\circ)$ is rather close to 2:1.

3. This ratio is close to 2 at 180° of the π, where the contribution of the direct photoproduction term in the π^+ channel is zero. We thank prof. C. Schaerf for giving us his data.

4. The cross section for π scattering $\pi^+ + p \to \pi+ + p$ is lower than the π^- scattering by more more than a factor 2 [10].

The values of $R_\pi(\Theta)$ are deduced by the measurements of Bulos and cow. [4] on the η, and by Bulos and cow. [9] and J. Helland and cow. [10] for the pion exchange and scattering.
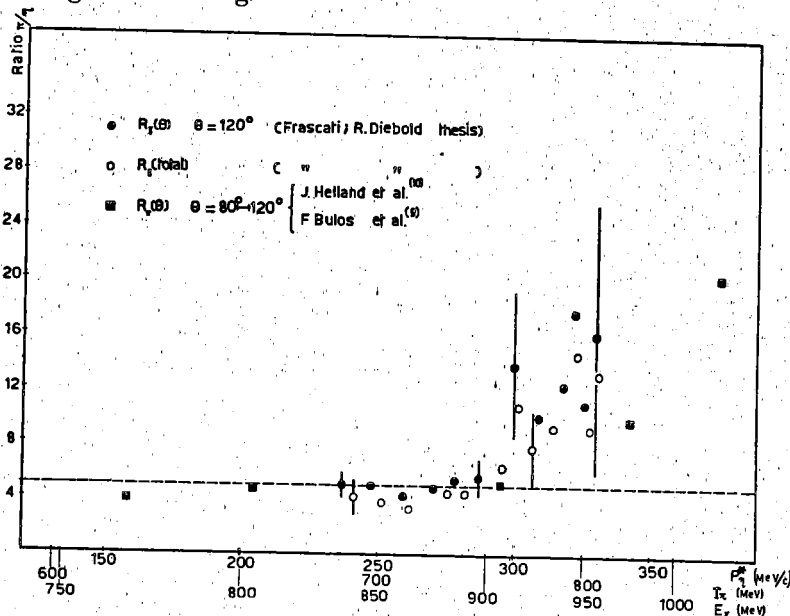

Fig. 5. Comparison between π and η, in photoproduction and scattering

The abscissa in Fig. 5 is linear with the momentum of the η in the c.m. system, P_η^*. The angle chosen for $R_\pi(\Theta)$ is an average in the interval $80°-120°$. The value R_π (total) ist less meaningful, due to the very large contribution of the forward scattering in (π^-, π^-) and (π^-, π°) processes. This large contribution is probably due to the inelastic processes which reflect themselves in the elastic channel as diffraction scattering [10]. Anyway, R_π(total) is reported in Fig. 6, and exhibits the same qualitative behaviour than all the R values in Fig. 5.

On the R values in Fig. 5 we can make two remarks:

a) In the region $140 < P_\eta^* < 300$ MeV/c the values of R_γ and R_π are rather low, rather constant, and rather close in absolute value.

This means that the η is rather abundant in this energy interval (one η every 4 or 5 pions); that it shares with the π its part in final states with a rather constant ratio; that the photoproduction and the scattering description of the η and the π in the standard isospin formalism are reciprocally consistent.

b) As we go beyond 300 MeV/c of P_η^*, the ratios R change and definitely increase, to show that pions (from the elastic channels and from single photoproduction) become relatively more abundant than η's.

The obvious remark is the following. Beyond 300 MeV/c of P_η^* (that is 910 MeV for the incident γ in the laboratory; 760 MeV for the kinetic energy

·of the π^- in the laboratory) the so called third resonance $F_{5/2}$ starts, to reach its maximum at ~ 1000 MeV of the incident γ. The pion increase is due to this resonance, and the fact is that the η does not seem to benefit of this resonance as well as the π.
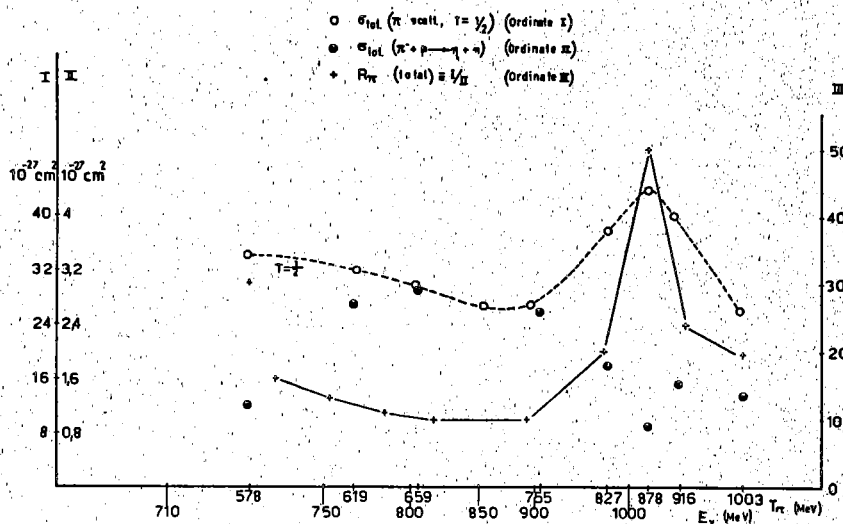

Fig. 6. Comparison π. η (total scattering cross section)

We must note that an high value of R in the region of the third resonance is not unexpected from the SU_3 symmetry [1] [2]. Dashen's argument tends to show that the photoproduction of the η is much lower than the π's at both the second and the third resonance.

It is important at this point, and this is our immediate future program, to study the angular distribution of the η in photoproduction. From these future measurements, and from the comparison with the scattering, one can eviden-tiate if the final states of the η-nucleon system are "something else" than the known pionic resonances and states.

This point of view is not incompatible with our results, and with the re-sults [4] from the scattering. It has been recently raised by Tuan [11] in con-nection with SU_6.

§ 5. - Conclusions

I) The existing data on the η, photoproduction and charge exchange, are consistent between themselves; they furnish a consistent $T = \frac{1}{2}$ picture in the region 800 - 1000 MeV of the incident γ ray.

II) The η production strongly decreases with the energy in the region of the third resonance ($F_{5/2}$), with respect to the single pion production.

III) This behaviour is consistent with the hypothesis that the contribution of the η among the final elastic states of the third resonance is rather low.

IV) It is necessary to continue our measurements, to see if the results arrive to indicate a definite distinction between the η-baryon and the π-baryon states [11].

We thank Prof. C. Pellegrini and Prof. C. Schaerf for helpful discussions.

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High Energy Photoproduction of Neutral Rho Mesons[1]

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We have made measurements of pion pair photoproduction for pair invariant masses in the range 0.3–1.5 BeV. The cross section for rho production is found to be large and is dominated by a diffraction-like mechanism.

Fig. 1 shows the experimental arrangement. Two spectrometers were pivoted about a target; each consisted of a quadrupole magnet with an obstacle in its center followed by arrays of counters to determine the direction and momentum of each pion. A PDP-1 computer analyzed the outputs of these counter