off-mass-shell effects, we therefore use the net decay rate to infer for the right-hand side of Eq. (19) the magnitude $(0.40\pm0.04)\times10^{-6}$. For the left-hand side the experimental magnitude is $(0.56\pm0.01)\times10^{-6}$.

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# PHOTOPRODUCTION OF THE ETA PARTICLE AT 800-1000 MeV. A COMPARISON BETWEEN THE $\pi N$ AND THE $\eta N$ SYSTEM.

C. Bacci, G. Penso, and G. Salvini

Istituto di Fisica dell'Università and Istituto di Fisica Nucleare, Sezione di Roma, Rome, Italy

and

C. Mencuccini and V. Silvestrini

Laboratori Nazionali del Comitato Nazionale per l'Energia Nucleare, Frascati, Italy

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Photoproduction on protons of the eta particle,

$$\gamma+p\to\eta+p, \tag{1}$$

has been measured at the Frascati 1100-MeV electron synchrotron, for incident photon energies from 800 to 1000 MeV. Our results allow a comparison with the pion production channel[1,2]

$$\pi^-+p\to\eta+n \tag{2}$$

as well as a comparison between the cross sections for pion and for eta production in both input channels, $\gamma+N$ and $\pi+N$ ($N$ stands for nucleon). A coherent picture in the $T=\frac{1}{2}$ isospin state is obtained. We find that the $\eta$-$N$ system is dominated at low energy by a state different from the known $\pi$-$N$ resonances, in good agreement with the suggested $S_{11}$ $\eta$-$N$ resonance.[3]

The experimental arrangement is similar in principle to the one used in our previous set of measurements,[4] but the apparatus has a much larger acceptance and a better resolution. The experimental layout is shown in Fig. 1. The $\gamma$-ray beam from the electron synchrotron is incident upon a 7.4-cm liquid $H_2$ target. Protons are detected in the proton telescope ($PT$), which is a combination of counters and four spark chambers.

On the line of flight of the $\eta$ there is a total-absorption lead-glass Cherenkov counter $C$ with an anticoincidence counter in front ($S_5$) to detect $\gamma$ rays. The energy of the $\gamma$ ray detected by $C$ is measured by a pulse-height analyzer and recorded on each photograph of the spark chambers. All our spark-chamber events are triggered by a coincidence between a proton in $PT$ and a photon in $C$. The eta is detected by two different methods, as already described by us.[4]

The first one (step method) is based on the energy distribution of the protons from Reaction (1) in $PT$. An example of this distribution is given in Fig. 2(a). It shows the energy spectrum of the protons detected in coincidence with a photon in $C$ of energy $E_C\geqslant420$ MeV. In this case most of the events come from Reaction (1). An alternative method for detecting process (1) consists in plotting the energy distribution of the protons for a "monochromatic" incident $\gamma$-ray beam at a given angle in the laboratory. This is simply obtained by taking the difference between the proton energy spectra at two different values of the maximum energy $E_0$ of the bremsstrahlung beam, normalized for the same number of equivalent quanta. This gives direct evidence

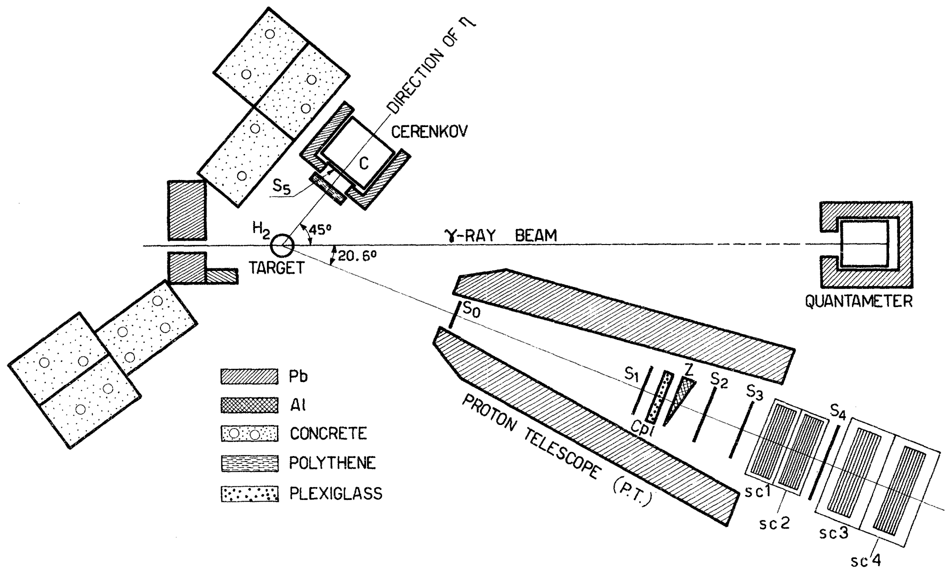


FIG. 1. Experimental layout. $S$: scintillation counters; $C$: total absorption lead glass Cherenkov; $SC$: spark chamber.

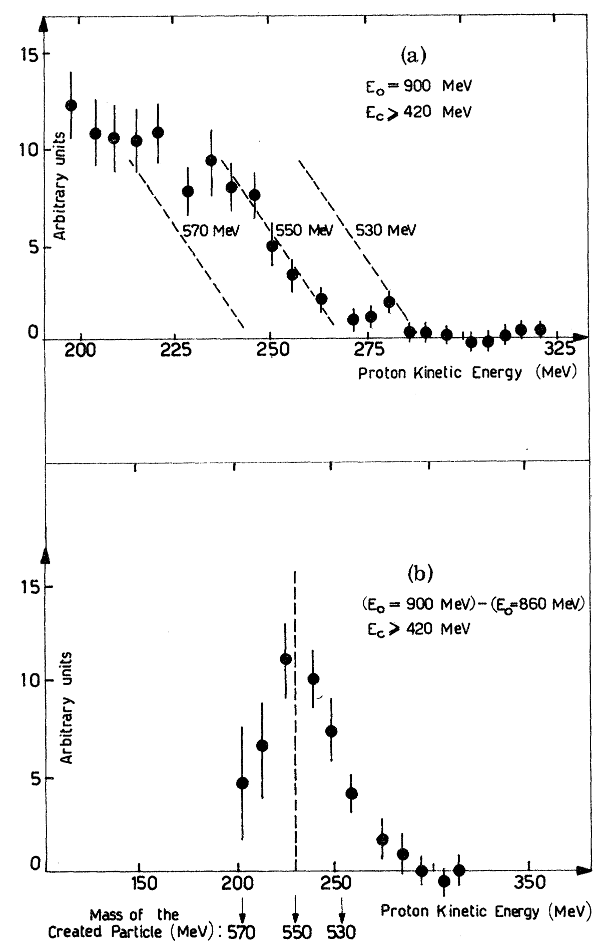


FIG. 2. (a) A typical result of the step method: Energy spectrum of protons in coincidence with a $\gamma$ ray in $C$ of energy $E_C \geq 420$ MeV. $E_0 = 990$ MeV. The expected position of the step for $m_\eta = 530$, 550, 570 MeV is shown. The angle of the proton telescope is 20.6°, with an acceptance of ±2.35°; the energy resolution is ~±3 MeV. (b) Difference between the proton spectra for $E_0 = 900$ MeV and $E_0 = 860$ MeV (see text).

of the existence of process (1). In Fig. 2(b), as an example, this difference for $E_0 = 900$ and 860 MeV is given. Reaction (1) must give a peak at the position corresponding to a mass of 548 MeV for the photoproduced particle, with an experimental width depending on our resolution and on the sharpness of our bremsstrahlung cutoff. In Fig. 2(b) the expected position of the "peak" for different mass values of the $\eta$ is shown; the experimental peak appears at the right place.

The second method ($\gamma$-rays method)[4] is based on the pulse-height analysis of the $\gamma$ ray detected in $C$. The interpretation of the results is in this case less certain due to the rather poor resolution of the Cherenkov counter. As we shall see, the two methods give very consistent results.

Results.—In Fig. 3 we report our results, that is, the cross section for process (1) in the interval 100°-120° for the c.m. angle of the $\eta$ and at different energies of the incident photon. The agreement between the results obtained by using the step method and the $\gamma$-ray method is very good; we stress, however, that the two measurements are obviously not completely independent.

The c.m. cross sections $(d\sigma/d\Omega^*)_{\gamma\gamma}$ (ordinates on the left in Fig. 3) are the cross sections for $\eta$ production when the $\eta$ decays by the $\gamma\gamma$ mode. They have been extracted from the events with a high pulse ($E_C \geqslant 420$ MeV) in $C$, so that mostly the $\gamma\gamma$ mode is observed. The differential cross section for all the decay modes of the produced eta can be immediately obtained when the branching ratio $\Gamma_{\gamma\gamma}/\Gamma_{\text{tot}} = \Gamma(\eta \rightarrow \gamma + \gamma)/\Gamma(\eta \rightarrow \text{all modes})$ is known. Using the value $\Gamma_{\gamma\gamma}/\Gamma_{\text{tot}} = 0.38$, which comes from the world average,[5] we obtain the values of

$$\frac{d\sigma}{d\Omega^*} = \left(\frac{d\sigma}{d\Omega^*}\right)_{\gamma\gamma} \frac{\Gamma_{\text{tot}}}{\Gamma_{\gamma\gamma}},$$

which are reported on the ordinates on the right in Fig. 3. The errors in Fig. 3 include the uncertainties due to background subtraction and an evaluation of possible systematic errors.[4] At the top of the diagram, the c.m. angle of the emitted eta is given. The results of our previous measurements[4,6] are also reported.

As shown in Fig. 3, the cross section for $\eta$ photoproduction goes down very fast with the energy of the producing photon in the interval 900 to 950 MeV. This decrease is analogous to, but sharper than, the behavior of the $\eta$ production cross section in the channel (2).

In the following we examine our results, and compare them to the $\pi$-$N$ channels, in order to determine if the $\eta$-$N$ final channel goes through the same resonances as the $\pi$-$N$ final channel, or whether there are also peculiar $\eta$-$N$ resonances. The comparison is therefore among the four processes (1), (2),

$$\gamma + N \rightarrow \pi + N, \tag{3}$$

and

$$\pi + N \rightarrow \pi + N \tag{4}$$

in the $T = \frac{1}{2}$ isospin state.

The processes (1) and (2) are pure $T = \frac{1}{2}$ states; the Reactions (3) and (4) are in general a mixture of $T = \frac{1}{2}$ and $T = \frac{3}{2}$. The $T = \frac{1}{2}$ part of process (4) is given by

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

where for instance $\sigma(\pi^-\pi^0)$ stands for $\sigma(\pi^- + p$

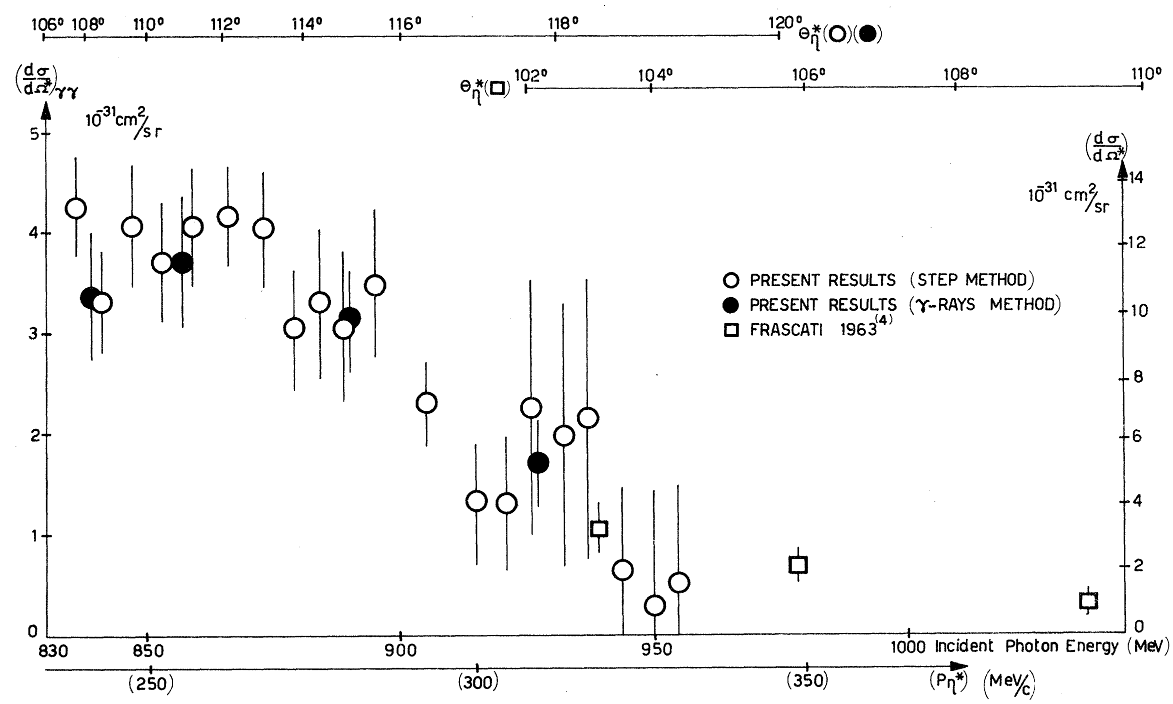


FIG. 3. Experimental results: $d\sigma/d\Omega^*(\eta \rightarrow \gamma + \gamma)$ (ordinates on the left) and $d\sigma/d\Omega^*(\eta \rightarrow \text{all modes})$ (ordinates on the right), as a function of $K$ (energy of the incident photon) and of $P_\eta{}^*$ (c.m. momentum of the $\eta$). In the upper scale the c.m. angle of the $\eta$ is shown.

$\rightarrow \pi^0 + n$). For the process (3) we are in an energy region in which the state $T = \frac{3}{2}$ seems to be negligible in the approximations of the present analysis.[7] So we assume

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

where $\sigma(\gamma\pi^0)$ stands for $\sigma(\gamma + p \rightarrow \pi^0 + p)$, etc.; $\sigma$ and $d\sigma/d\Omega^*$ are the total and differential cross sections. Then we can calculate the ratios

$$R_\gamma(\theta) = \frac{(d\sigma/d\Omega^*)_{\gamma, T=\frac{1}{2}}}{(d\sigma/d\Omega^*)_{\gamma, \eta}}$$

and

$$R_\pi(\theta) = \frac{(d\sigma/d\Omega^*)_{\pi, T=\frac{1}{2}}}{(d\sigma/d\Omega^*)_{\pi, \eta}}.$$

In Fig. 4 the values of $R_\gamma(\theta)$ and $R_\pi(\theta)$ are given, as a function of $P_\eta^*$, momentum of the $\eta$ in the c.m. system. They are deduced from our present and previous[4,6] measurements and from the results of other authors.[1,8-10] $R_\gamma(\theta)$ and $R_\pi(\theta)$ have the same behavior as functions of energy, and their absolute values are very close to each other, consistent with the assumption that the reactions we are considering are all in a $T = \frac{1}{2}$ isospin state.

In the same figure $R_\gamma$(total) and $R_\pi$(total) are also shown; they have the same meaning as $R_\gamma(\theta)$ and $R_\pi(\theta)$, the ratio being now between total cross sections. $\sigma(\gamma\eta)$ has been evaluated as $(d\sigma/d\Omega^*)_{\gamma\eta} \times 4\pi$, this assumption being supported by the isotropy[11] of $(d\sigma/d\Omega^*)_{\gamma\eta}$ around $P_\eta^* = 200$ MeV/$c$ and of $(d\sigma/d\Omega^*)_{\pi\eta}$ up to $P_\eta^* \approx 300$ MeV/$c$.[1]

The low values of $R_\gamma$ and $R_\pi$ in the region $140 \leq P_\eta^* \leq 300$ MeV/$c$ (~5-10) can hardly[12] be explained on the hypothesis that the second resonance $D_{13}N^{**}$(1512 MeV) is the dominant state of the $\eta$-$N$ system. In fact various evidence indicates that the coupling constant $G_{\eta NN^{**}} \approx 0.2 G_{\pi NN^{**}}$ or less, and the angular-momentum factors of the $D_{13}$ state favor the $\pi^0$ by a factor ~200.[12] The high production rate of the $\eta$ in channel (2) near threshold and the isotropic angular distribution[1] have already led to the hypothesis[3] that an $S_{11}$ $\eta$-$N$ resonance exists, with $T = J = \frac{1}{2}$. The energy is around 1520 MeV; the width $\Delta$ is $\leq$150 MeV. From our data it appears that the cross section for process (1) goes down faster than in process (2) at the same angle. This gives a stronger evidence in favor of a resonant behavior. The possible value of $\Delta$ as extracted from our data agrees with the hypothesis of Hendry and Moorhouse.[3]

In the region $P_\eta^* \geq 300$ MeV/$c$ other states could be present, beyond a possible tail of the state $S_{11}$.

Our values do not exclude the possible presence of the third $F_{15}$ $\pi$-$N$ resonance. Using Dashen's formalism,[12] our results, and the

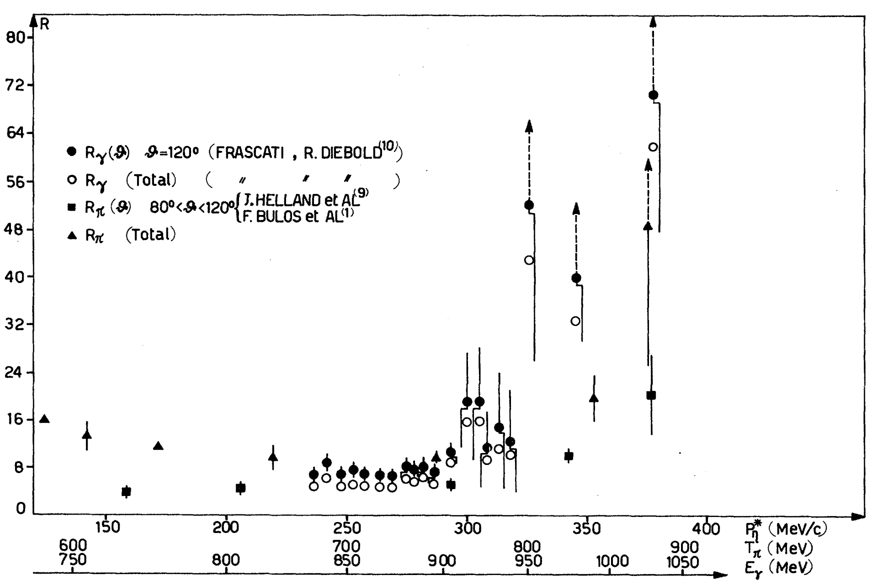


FIG. 4. The ratio of $\pi$- to $\eta$-production cross sections, as a function of the c.m. momentum of the $\eta$. The laboratory energy of the particle producing the reaction is also reported. $R_\gamma$ and $R_\pi$ are defined in the text.

results of Ref. 10, we find an upper limit for the ratio of the $\pi$ and $\eta$ couplings with the $N^{***}$ third resonance:

$$\frac{{G_{\eta NN^{***}}}^2}{{G_{\pi NN^{***}}}^2} \leq 3\frac{(d\sigma/d\Omega^*)_{\gamma\eta}}{(d\sigma/d\Omega^*)_{\gamma\pi^0}} \approx 0.15.$$

This value does not disagree with unitary symmetry predictions.[12]

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