PHOTOPRODUCTION OF ETA MESONS FROM 950 TO 1100 MeV†

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(Received 18 July 1966)

This is a report on the first part of an experiment on photoproduction of η mesons at the Caltech 1.5-BeV electron synchrotron.[1] The η meson, whose mass and quantum numbers were established in bubble-chamber work in πN and KN interactions ($M_\eta = 548 \pm 1$ MeV, $J^{PG} = 0^{-+}$, $C = +1$), was later observed in photoproduction by Bacci et al. at Frascati.[2] The purposes of our experiment were to extend cross-section data to higher energies and, specifically, to investigate a possible contribution of the isobar diagram, Fig. 1, to the photoproduction mechanism. Since the space-time properties of the η meson are the same as those of the π^0 [both particles occupy the weight-2 position in the pseudoscalar-meson octet of SU(3)], the cross-section contributions due to this diagram should, except for kinematical differences, closely resemble each other. Using unbroken SU(3) the invariant coupling ratio can be predicted and a comparison carried out if the contribution of the diagram can be isolated.[3]

The N^{***}(1688 MeV) has quantum numbers $T = \frac{1}{2}$, $J^P = \frac{5}{2}^+$. The angular-distribution data from π^0 photoproduction[4] show the dominance of an $F_{5/2}$ wave, with maxima at 40° and 140° c.m. angles. Consequently, we chose c.m. angles around 45° for our investigation of η photoproduction. Measurement at 90° c.m. would make isolation of the contribution from the diagram in Fig. 1 hopeless.

The observation of η production by photons having a bremsstrahlung spectrum is handicapped by the presence of large competing background processes. We, therefore, chose a detection method with the intention of optimizing determination of the kinematical parameters of the final state. All final-state particles of the process

$$\gamma + p \to p + \eta^0(\eta^0 \to 2\gamma)$$

were detected [branching ratio $\Gamma(\eta \to 2\gamma)/\Gamma(\eta \to \text{all decays}) = 38.6\,\%$ [5]]. The general layout of the experiment is as follows: the bremsstrahlung beam from the synchrotron, collimated and passed through a sweeping magnet, interacts in a liquid hydrogen-target (containing approximately 1 g/cm^2 liquid hydrogen) before being monitored by a Wilson-type quantameter. The recoil protons emerging from the target pass through a sequence of scintillation counters and thin-foil spark chambers, and are required to stop in a range-determining thick-plate spark chamber. This system fully determines the four-momentum of the recoil proton.[6]

The η is identified by detecting both decay photons from its $\gamma\gamma$ decay mode, observed in a plane perpendicular to the production plane. Each decay photon was detected in shower counters consisting of lead-lucite Čerenkov sandwiches.[7] The shower counters were placed at the lab angles for the symmetrical decay of the η ($\sin\frac{1}{2}\theta_{\text{sym}} = m_\eta/E_\eta$). Each shower-counting system is preceded by (a) two veto counters in fast coincidence, to insure that a neutral particle initiated the observed pulse in the shower counter, (b) two radiation lengths of lead which convert most of the photons, and (c) a bank of scintillators which detect the converted photon and define the lab production angle. Information obtained from this apparatus, together with the four-momentum of the proton, overdetermines the entire final state sufficiently to make a suppression of backgrounds effective. A fast three-fold master coincidence ($\gamma_1\gamma_2 p$) triggered the spark chambers; all data obtained were digitally displayed in the photographic frame and constantly monitored with a closed-circuit TV system. Pulse-height calibrations were performed at regular intervals on all critical counters. The constancy of counting rates of individual counters and coincidence outputs provided a close check on the performance of the fast logic.

Experimental data were obtained for incoming γ energies between 950 and 1100 MeV at η production angles around 45° in the c.m. sys-

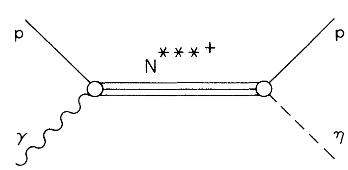


FIG. 1. Isobar diagram.

tem (the N^{***} isobar is photoproduced at photon energies about 1025 MeV). Data were taken at three overlapping kinematical settings (see Table I), thus permitting internal consistency checks.

For an event to be accepted, we demand clear tracks in all chambers, stopping of the proton in the range chamber, proper energy deposited in the shower counters, and conversion of both η decay photons. We fix the full kinematics by reconstructing the proton energy and angle, T_p and θ_p, from the chamber information, and the η angle, θ_η, from the scintillator hodoscope information. Then we can compute the energy of the incoming photon, k, and the mass of the particle produced (assuming it decayed into two γ's). Figure 2(a) shows a plot of the masses obtained in this manner. There is a well-defined peak, containing about 500 fully determined events, on top of a broader background. Figure 2(c) displays the pulse heights from the shower counter for events within the peak, and a calibration peak obtained from fast π's; also displayed are distributions obtained from previous calibration runs in a monoenergetic photon beam for comparison.

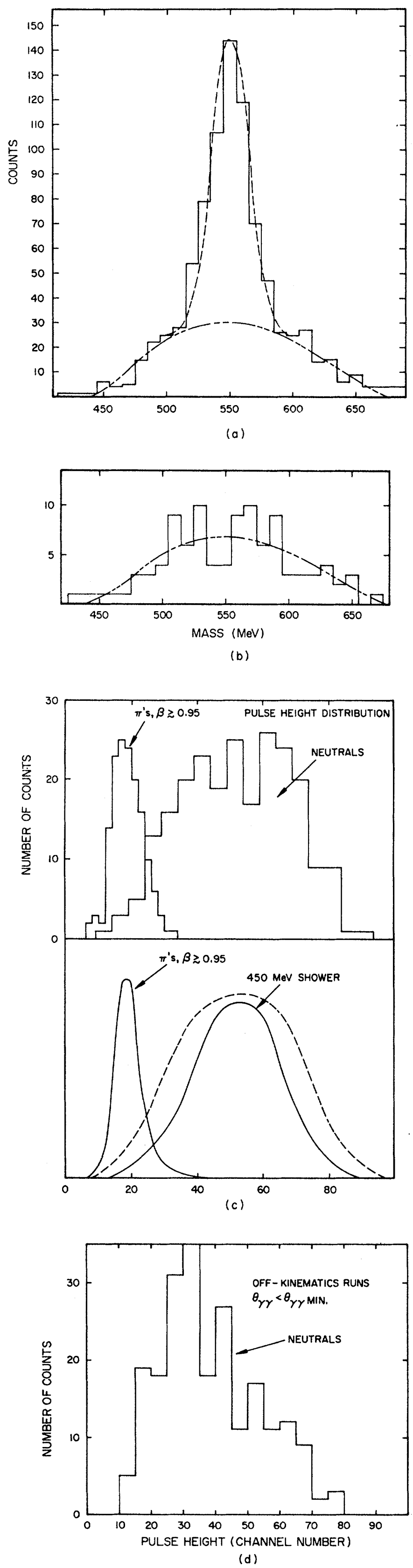
To obtain a clear background determination, data were taken at a kinematical setting unattainable for good events (by decreasing the γ-γ correlation angle below the minimum symmetrical case). The resulting background masses are shown in Fig. 2(b), and the corresponding spectrum in Fig. 2(d). The background mass spectrum exhibits a smooth, nonpeaked behavior characteristic of our detection efficiency. The pulse-height spectrum, Fig. 2(d), differs from that of the "good" events and is consistent with the decays $\eta \to \pi^0+\gamma+\gamma$ and $\eta \to 3\pi^0$ and $2\pi^0$ production.

The shape of the η peak in the mass plot can be precisely calculated from known data on multiple scattering of the recoil protons, range resolution, and angular uncertainties, the only adjustable parameter being the number of events contained. A background subtraction is, therefore, possible without danger of serious error. Moreover, background events were artificially generated from the processes

$$\gamma+p \to 2\pi^0+p,$$

Table I. Differential cross section for $\gamma+p\to p+\eta$ at 45° c.m. Results of three separate runs and combined results are given.

Run	k (MeV)	Counts Before subtraction	Counts After subtraction	$d\sigma/d\Omega$ (μb/sr)
1	940	22	15	0.248 ± 0.078
	965	57	48	0.245 ± 0.040
	990	57	48	0.206 ± 0.033
	1015	39	31	0.206 ± 0.043
	1040	24	17	0.254 ± 0.074
2	940	19	6	0.257 ± 0.187
	965	67	39	0.254 ± 0.055
	990	82	53	0.163 ± 0.029
	1015	82	57	0.152 ± 0.025
	1040	66	44	0.149 ± 0.029
	1065	36	23	0.146 ± 0.039
3	990	25	5	0.126 ± 0.126
	1015	36	16	0.156 ± 0.060
	1040	52	35	0.204 ± 0.043
	1065	51	38	0.212 ± 0.041
	1090	35	26	0.216 ± 0.050
all runs	940			0.249 ± 0.072
	965			0.248 ± 0.032
	990			0.180 ± 0.021
	1015			0.164 ± 0.020
	1040			0.175 ± 0.023
	1065			0.177 ± 0.028
	1090			0.216 ± 0.050



$$\gamma+p\to\eta+p\to 3\pi^0+p,$$

and

$$\gamma+p\to\eta+p\to\pi^0+2\gamma+p$$

in a Monte Carlo calculation, in which the only adjustable parameter was the $2\pi^0$ production cross section. This yielded good fits to the observed backgrounds with $\sigma_{\text{tot}}(\gamma+p\to 2\pi^0)\approx 42$ μb; this number is consistent with what little information exists on 2π photoproduction in this energy region,[8] and also accounts for the results of our background runs.

The mass plot displayed in Fig. 2(a) shows the fitted background and the η peak sitting on top, with the computed peak shape as a check. The mass of the η according to this experiment is

$$m_\eta = 549.8\pm 1.5 \text{ MeV}.$$

Since the shape of the peak can be computed from precisely known data, we can also give an upper limit to the width of the η through quadratic subtraction of computed and measured

FIG. 2. (a) Mass plot of photoproduced particles decaying into 2γ's. The peak due to the 2γ decay of η mesons appears above a broad background. The dashed line indicates the result of a Monte Carlo calculation simulating our experimental setup, for mass 549 MeV, where the only fitted parameter is the area contained. The dash-dotted line indicates a typical counter-efficiency distribution expected from final states $2\pi^0$, $\eta\to 3\pi^0$, and $\eta\to\pi^0+\gamma+\gamma$. Its shape is sensitive to the model employed for the Monte Carlo simulation of background events. The subtraction was performed according to the fit shown, which also satisfies our off-kinematics background runs shown in Fig. 2(b). (b) Mass plot of background events taken in off-kinematics position, with the shower counters at a smaller-than-minimum correlation angle. The shape of the displayed curve is the same as that of the background fit in Fig. 2(a). No η peak is visible. (c) Upper plot: typical unsubtracted pulse-height distribution in shower counters for on-kinematics events, together with calibration distribution taken with fast π's. Lower plot: corresponding distributions from calibration runs in monoenergetic tagged photon beam, and with 800 MeV/c π's. Typical shower energy in this experiment is 450 MeV. Dashed line indicates expected widening of distribution due to variation of photon energy across counter face. The two plots are seen to be closely similar. (d) Typical pulse-height distribution in shower counters for an off-kinematics run. The spectrum peaks at lower energies, as expected from multineutral final states.

widths of the peak. It is $\Gamma_\eta \leq 15$ MeV. Both these measurements are being improved in a current run with better statistics.[9]

The cross section was computed with the aid of a Monte Carlo program for the determination of the geometrical detection efficiency for η's decaying into two photons. The individual results for various runs are given in Table I; the final values over the range of our experiment may be seen in Fig. 3. For a comparison, we show recent data taken around 90° c.m. at lower energies at Stanford[10] and Frascati.[11]

Several remarks on Fig. 3 may be made. The general features of η photoproduction resemble the pattern observed in $\pi^- + p \rightarrow \eta + n$ by Bulos et al.[12] and by the Berkeley group.[13] The sharp rise above threshold and the monotonic decrease above 1600 MeV c.m. energy seem to show up in both the γp and $\pi^- p$ initial states. Our data, taken at 45°, suggest a smooth continuation of the Stanford points taken around 90°. The data of Richards[13] on the angular distribution in $\pi^- p$ at these energies shows a slight forward peaking, and the photoproduction data seems to exhibit a similar behavior.

A maximum around $k = 1025$ MeV ($W = 1688$ MeV), which would be expected at 45° if decay of the N^{***+}-dominated η photoproduction similarly to the π^0 case, clearly does not appear. On the other hand, there is no downward slope between 950 and 1100 MeV. Whether this is due to the presence of a shoulder caused by

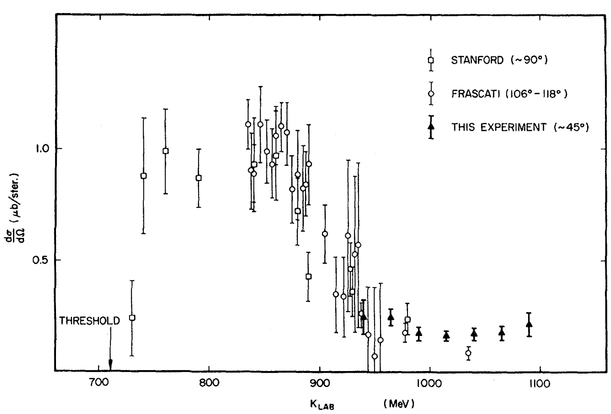


FIG. 3. Differential cross section for $\gamma + p \rightarrow p + \eta$. The Frascati[6] and Stanford[5] data were taken at angles around 90° c.m. This experiment was performed at 45° c.m. The energy dependence of the cross section resembles the $\pi^- + p \rightarrow n + \eta$ data.[7-9] An enhancement in the 45° data, which would be expected from $N^{***}(k = 1025$ MeV) decay according to Fig. 1, is not seen.

N^{***} decay, or whether there is a buildup towards a small peak around 1220 MeV as suggested in Ref. 9 (but not observed by the Brookhaven group[12]), remains to be decided by further experiment. Data are presently being taken to determine cross sections at higher energies and at larger production angles.

We wish to acknowledge helpful conversations with R. L. Walker and A. V. Tollestrup. Walter Nilsson was our invaluable assistant in setting up the experiment.

†Work supported in part by the U. S. Atomic Energy Commission. Prepared under Contract No. AT(11-1)-68 for the San Francisco Operations Office, U. S. Atomic Energy Commission.

[1]A preliminary account of this work was presented in C. A. Heusch, C. Y. Prescott, E. D. Bloom, and L. S. Rochester, in Electron and Photon Interactions at the High Energies, Invited Papers Presented at the International Symposium, Hamburg, 1965 (Springer-Verlag, Berlin, Germany, 1965).

[2]C. Bacci, G. Penso, G. Salvini, A. Wattenberg, C. Mencuccini, R. Querzoli, and V. Silvestrini, Phys. Rev. Letters 11, 37 (1963).

[3]R. F. Dashen, Nuovo Cimento 32, 469 (1964); C. A. Heusch, C. Y. Prescott, and R. F. Dashen, to be published.

[4]R. Diebold, Phys. Rev. 130, 2089 (1963).

[5]The neutral branching ratios of η decay are not well established; we take here the best currently available value from A. H. Rosenfeld, A. Barbaro-Galtieri, W. H. Barkas, P. L. Bastien, J. Kirz, and M. Roos, Rev. Mod. Phys. 37, 633, (1965).

[6]The accuracy of the measurements of proton recoil angle ($\Delta\theta_p = 0.6°$ to $1.0°$) and kinetic energy ($\Delta T_p/T_p = 3$-$5\,\%$) is dependent on T_{p_1} and improves with increasing energy.

[7]C. A. Heusch and C. Y. Prescott, Nucl. Instr. Methods 29, 205 (1964).

[8]J. V. Allaby, H. L. Lynch, and D. M. Ritson, Phys. Rev. 142, 887 (1966).

[9]These values should be taken here as consistency checks only; they check well with the best currently available data of $m_\eta = 548.8 \pm 0.5$ MeV; $\Gamma_\eta < 10$ MeV (cf. Ref. 5).

[10]R. Prepost, D. Lundquist, and D. Quinn, in Electron and Photon Interactions at the High Energies, Invited Papers Presented at the International Symposium, Hamburg, 1965 (Springer-Verlag, Berlin, Germany, 1965).

[11]C. Bacci, G. Penso, C. Mencuccini, G. Salvini, and V. Silverstrini, Phys. Rev. Letters 16, 157 (1966).

[12]F. Bulos et al., Phys. Rev. Letters 13, 486 (1964).

[13]W. B. Richards et al., Phys. Rev. Letters 16, 1221 (1966).