in providing desired beam characteristics, magnetic measurements, etc. throughout this project.

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[5]The normalization factor $[\sigma_{tot}(20\ \mathrm{BeV}/c)/\sigma_{tot}(p)]^2$ is the same (within 2%) at any P for $\pi^+ + p$ and $\pi^- + p$, and its average is about 1.15. Therefore, the fits in Fig. 1 are consistent with a small fraction for the quantity

$$\frac{(d\sigma/dt)(\pi^- + p) - (d\sigma/dt)(\pi^+ + p)}{\frac{1}{2}[(d\sigma/dt)(\pi^- + p) + (d\sigma/dt)(\pi^+ + p)]}$$

at low t which increases somewhat with increasing t. Hence the data are consistent with the usual assignment of only a small effect due to the ρ pole at least at low t.

EXPERIMENTAL DETERMINATION OF THE NEUTRAL BRANCHING RATIOS OF THE η MESON*

Frank S. Crawford, Jr., and L. J. Lloyd
Lawrence Radiation Laboratory, University of California, Berkeley, California

and

Earle C. Fowler
Duke University, Durham, North Carolina
(Received 13 May 1963)

The generally accepted values for the quantum numbers of the η meson are given by $J^PI^G = 0^-0^+$.[1] These assignments have been established primarily through studies of the Dalitz-Fabri plot for the decay $\eta \to \pi^+\pi^-\pi^0$.[2] The existence of the expected mode $\eta \to \pi^+\pi^-\gamma$ has recently been established, with a branching ratio given by

$$\Gamma(\eta \to \pi^+\pi^-\gamma)/\Gamma(\eta \to \pi^+\pi^-\pi^0) = 0.26 \pm 0.08.^3 \quad (1)$$

The existence of the mode $\eta \to \gamma\gamma$ has been established by using etas produced in a heavy-liquid bubble chamber[4]; but its relative probability has not been determined prior to the experiment reported here. The expected decay mode $\eta \to 3\pi^0$ is difficult to observe[4] and has not been established by direct observation prior to this experiment. However, the ratio (neutral/charged) = $\Gamma(\eta \to \text{neutrals})/\Gamma(\eta \to \pi^+\pi^-x^0)$, with x^0 unresolved into π^0 and γ, has been determined in several experiments by counting "missing neutrals."[2] An average over these experiments gives (neutral/charged) = 2.7 ± 0.6. The neutrals should correspond to $\eta \to \gamma\gamma$ plus $\eta \to 3\pi^0$ if the η quantum numbers are 0^-0^+.[5]

In the experiment described here we confirm the existence of the decay mode $\eta \to \gamma\gamma$, and find a branching ratio

$$\Gamma(\eta \to \gamma\gamma)/[\Gamma(\eta \to \pi^+\pi^-\pi^0) + \Gamma(\eta \to \pi^+\pi^-\gamma)] = 0.99 \pm 0.48. \quad (2)$$

We also establish directly the existence of the mode $\eta \to 3\pi^0$, and find

$$\Gamma(\eta \to 3\pi^0)/[\Gamma(\eta \to \pi^+\pi^-\pi^0) + \Gamma(\eta \to \pi^+\pi^-\gamma)] = 0.66 \pm 0.25. \quad (3)$$

The sum of our results (2) and (3) gives (neutral/charged) = 1.65 ± 0.53, in only fair agreement with the result 2.7 ± 0.6 others have obtained by counting missing neutrals.[2]

Calculations based on the model $\eta \to \rho_1^0 + \rho_2^0$, $\rho_1^0 \to \gamma$, $\rho_2^0 \to \pi^+\pi^-$ predict $\Gamma(\eta \to \pi^+\pi^-\gamma)/\Gamma(\eta \to \gamma\gamma) \approx 1/4$.[6] If we combine our results (2) with our earlier result (1), we find

$$\Gamma(\eta \to \pi^+\pi^-\gamma)/\Gamma(\eta \to \gamma\gamma) = 0.21 \pm 0.12.$$

Since $\eta \to 3\pi$ should go into the 3π state with $I = 1$, one expects $\Gamma(\eta \to 3\pi^0)/\Gamma(\eta \to \pi^+\pi^-\pi^0) = 3/2$. Phase-space corrections and dynamical calculations based on a comparison of the Dalitz-Fabri plots of $\eta \to \pi^+\pi^-\pi^0$ and $K \to 3\pi$ yield a predicted value of 1.68 ± 0.05 for this ratio.[7] Combining our experimental results (1) and (3), we obtain

$$\Gamma(\eta \to 3\pi^0)/\Gamma(\eta \to \pi^+\pi^-\pi^0) = 0.83 \pm 0.32,$$

in rather poor agreement with the prediction.

The remainder of this Letter is devoted to experimental details.

The η's were produced in the Alvarez 72-inch hydrogen bubble chamber via the reaction $\pi^+ + p \to \pi^+ + p + \eta$, using incident π^+ of 1170 MeV/c. We have analyzed 1500 two-pronged ($2P$) events having an associated γ-ray conversion in hydrogen, and 4500 four-pronged ($4P$) events from the same sample of film. The $4P$ events include $\pi^+ p \to \pi^+ p \pi^+ \pi^- x^0$, with $x^0 = \pi^0$ or γ. This event type is almost entirely due to $\pi^+ p \to \pi^+ p \eta$, $\eta \to \pi^+\pi^- x^0$.[3] The elimination of background due to $\pi^+ p \to \pi^+ p \pi^+ \pi^-$ and the resolution of x^0 into π^0 and γ have been described elsewhere.[3] In the experiment reported here the decays $\eta \to \pi^+\pi^- x^0$ provide the "denominators" for the neutral branching ratios.

We study the neutral decay modes by two independent methods.

In the first method we look for an e^+e^- pair resulting from internal conversion of one γ ray (virtual), γ_V, coming from $\eta \to \gamma\gamma$ or $\pi^0 \to \gamma\gamma$, where the π^0 may have come from η decay. One then has a $4P$ track configuration $\pi^+ p \to \pi^+ p e^+ e^- x^0$, where x^0 represents all undetected neutrals. We write this process as $\pi^+ p \to \pi^+ p y^0$, $y^0 \to \gamma_V + x^0$, $\gamma_V \to e^+e^-$. For $y^0 = \eta$ we consider two decay modes. (a) We may have $\eta \to 3\pi^0 = 2\pi^0 + \pi^0 \to 2\pi^0 + \gamma_R + \gamma_V = x^0 + \gamma_V$, so that $x^0 = 2\pi^0 + \gamma_R$, where γ_R is a real γ ray. The invariant mass $m(e^+e^-) = m(\gamma_V)$ therefore ranges between $2m(e) = 1.1$ and $m(\pi^0) = 135$ MeV/c^2. The distribution in $m(e^+e^-)$ and the branching ratio $\Gamma(\pi^0 \to \gamma_R + \gamma_V)/\Gamma(\pi^0)$ are well known.[8,9] We use only events with $m(e^+e^-) < 30$ MeV/c^2; this includes 85% of the decays $\pi^0 \to \gamma_R + \gamma_V$, and a fraction 0.0101 of all π^0 decays.[8,9] (b) In the second mode we have $\eta \to \gamma_R + \gamma_V = x^0 + \gamma_V$, so that $x^0 = \gamma_R$ and $m(x^0) = 0$; $m(e^+e^-)$ ranges between $2m(e)$ and $m(\eta) = 548$ MeV/c^2. The branching ratio $\Gamma(\eta \to \gamma_R + \gamma_V)/\Gamma(\eta \to 2\gamma_R)$ is insensitive to the dynamical details of the decay.[8] The criterion $m(e^+e^-) < 30$ MeV/c^2 includes 62% of the decays $\eta \to \gamma_R + \gamma_V$ and a fraction 0.0101 of all decays $\eta \to \gamma + \gamma$, with $\gamma = \gamma_R$ or γ_V. That we obtain the same fraction 0.0101 for both π^0 and η is not an accident.[10]

In the second method we look for an e^+e^- pair due to hydrogen (H) conversion of a real γ ray in association with a two-pronged track configuration $\pi^+ p \to \pi^+ p y^0$. Then we have $y^0 \to \gamma_R + x^0$ (x^0 = undetected neutrals), and $\gamma_R + \text{H} \to e^+e^- + \text{H}$. We impose the criterion $L_\gamma < 40$ cm on the path length L_γ of γ_R, and the criterion $p_\text{H} < 15$ MeV/c on the recoil momentum p_H of H in the conversion process. To determine the detection probability for γ_R we make use of several hundred events $\pi^+ p \to \pi^+ p \pi^0$. By counting internal conversion events $\pi^0 \to \gamma_R + \gamma_V$, $\gamma_V \to e^+e^-$, we determine the number of π^0 produced. We choose a suitable subsample having the same distribution in p_γ and θ_γ as that calculated for $\pi^+ p \to \pi^+ p \eta$, $\eta \to 2\gamma_R$, or for $\eta \to 3\pi^0 \to 6\gamma_R$. The observed number of H conversions from this subsample determines the over-all detection efficiency, including the effects of H-conversion cross section, fiducial volume, and scanning efficiency. We find the probability for one of the γ_R to convert (subject to our criteria) is 0.0244 for γ's from $\eta \to 2\gamma_R$ and 0.0248 from $\pi^0 \to 2\gamma_R$, where π^0 comes from $\eta \to 3\pi^0$.

The total number of events ($4P$ plus $2P$) expected from one "average" decay $\eta \to \gamma + \gamma$ is then $0.0101 + 0.0244 = 0.0345$. The expected number from one decay $\eta \to 3\pi^0$ is $3(0.0101 + 0.0248) = 0.105$.

In Fig. 1 we plot the invariant $m^2(y^0)$ versus $m^2(x^0)$ for each event $\pi^+ p \to \pi^+ p y^0$, $y^0 \to \gamma + x^0$, where x^0 is the missing four momentum. Both internal-

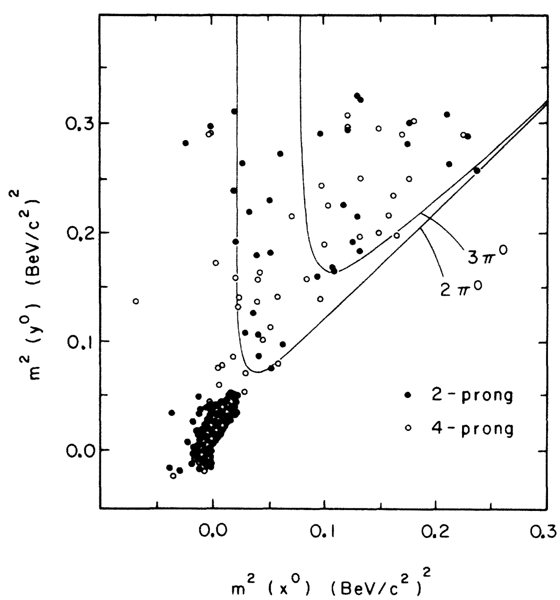

FIG. 1. Plot of $m^2(y^0)$ versus $m^2(x^0)$, where $\pi^+ + p \to \pi^+ + p + y^0$, $y^0 \to \gamma + x^0$; γ is a detected γ ray (real or virtual) and x^0 = missing neutrals. Kinematical limits are indicated for $y^0 = 2\pi^0$ and $y^0 = 3\pi^0$.

conversion and H-conversion events are included.[11] We require the calculated error in $m^2(y^0)$, $\delta m^2(y^0)$, to be less than 0.014 $(\mathrm{BeV}/c^2)^2$. Since the four-momentum y^0 is calculated as "missing" in $\pi^+p \to \pi^+py^0$, the error cutoff does not affect branching ratios. (This cutoff is also applied to the denominator events, $y^0 \to \pi^+\pi^-x^0$.) Kinematical limits are indicated for $y^0 = 2\pi^0$ and for $y^0 = 3\pi^0$. For $y^0 = 2\pi^0$ it is easily shown that the distribution in $m^2(x^0)$ is flat for any value of $m^2(y^0)$. (This is not so for $y^0 = 3\pi^0$; the regions near the kinematical limits are depopulated by a phase-space factor.) Inspection of Fig. 1 shows a large cluster of events at $m^2(y^0) = m^2(\pi^0) = 0.0182$ $(\mathrm{BeV}/c^2)^2$, $m^2(x^0) = m^2(\gamma) = 0$, corresponding to $\pi^+p \to \pi^+p\pi^0$, $\pi^0 \to \gamma\gamma$. The remaining events are seen to be mostly due to $y^0 = 2\pi^0$.

To demonstrate the presence of η production and decay, we plot in Fig. 2 the number of events versus $m^2(y^0)$, for $m^2(y^0) > 0.08$ $(\mathrm{BeV}/c^2)^2$. The solid histogram gives the expected distribution in $m^2(y^0)$ for $y^0 = 2\pi^0$. Its shape is determined from 2600 events of the type $\pi^+p \to \pi^+py^0$, $y^0 = \pi^+\pi^-$. It is normalized by a least-squares fit to the first five histogram intervals in Fig. 2.[12] We see that the solid histogram fits all the data except for a pronounced peak at the η mass. Between $m^2(y^0) = 0.28$ and 0.32, we predict (from the solid histogram) 4.3 ± 0.6 events[13] from $y^0 = 2\pi^0$. We find 17 events, however. We conclude that most of the 17 events are due to η production and decay.

In Fig. 3 we plot the distribution in $m^2(x^0)$ for the 17 events having $0.28 < m^2(y^0) < 0.32$, along with the kinematical limits for $y^0 = \gamma\gamma$, $3\pi^0$, and $2\pi^0$. The events separate clearly into five $\gamma\gamma$ and twelve $3\pi^0$ events. We prorate the 4.3 ± 0.6 predicted background counts from $2\pi^0$ according to the overlap of the allowed regions in $m^2(x^0)$, tak-

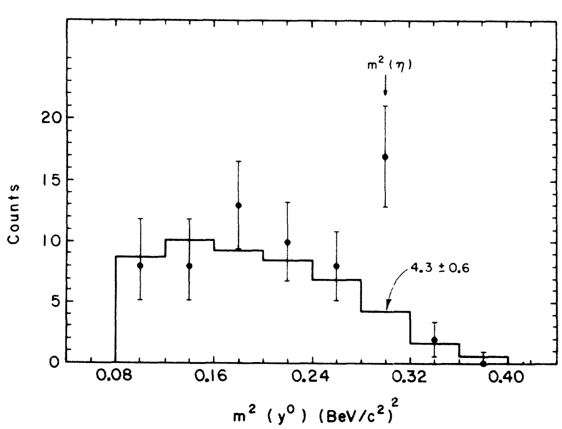

FIG. 2. Distribution in $m^2(y^0)$.

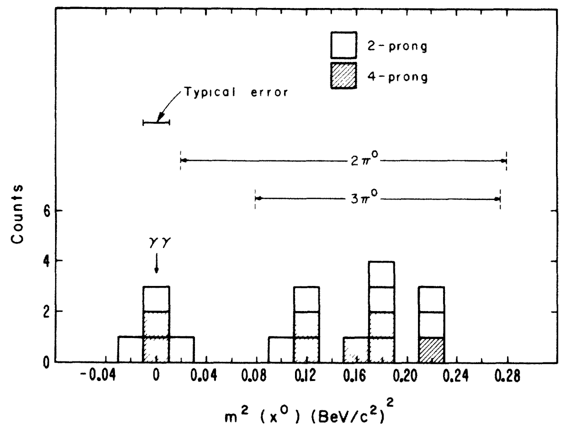

FIG. 3. Distribution in $m^2(x^0)$ for events having $0.28 < m^2(y^0) < 0.32$ $(\mathrm{BeV}/c^2)^2$.

ing into account the measurement errors, and thus assign 0.33 ± 0.05 background $(2\pi^0)$ counts to the $\gamma\gamma$ region, 2.50 ± 0.05 to $3\pi^0$, and 1.47 ± 0.20 to the region between $\gamma\gamma$ and $3\pi^0$. (Inspection of Fig. 3 shows that none of the predicted 1.47 counts is realized. This is a reasonable Poisson fluctuation.) We combine the observed $2P$ and $4P$ events (with background subtracted) and the detection factors 0.0345 for $\gamma\gamma$ and 0.105 for $3\pi^0$ to get the effective number of decays $N(\eta \to \gamma\gamma) = (5 - 0.33)/0.0345$, and $N(\eta \to 3\pi^0) = (12 - 2.50)/0.105$.

The "denominator" $N(\eta \to \pi^+\pi^-x^0)$, with $x^0 = \pi^0$ or γ, is obtained from $4P$ events $\pi^+p \to \pi^+py^0$, where $y^0 = a^+b^-x^0$. We assume $a^+ = \pi^+$ and $b^- = \pi^-$, provided the invariant $m(a^+b^-)$ satisfies $m(a^+b^-) > 100$ MeV/c^2 under the mass assignments $m(a^+) = m(b^-)$ = electron mass, for both assignments of the π^+. This criterion eliminates internal-conversion pairs $a^+b^- = e^+e^-$, and removes only 5% of the events $y^0 = \pi^+\pi^-x^0$.[3] The procedures by which we eliminate events $\pi^+p \to \pi^+p\pi^+\pi^-$ from our sample give an additional 10% loss in events $y^0 = \pi^+\pi^-x^0$.[3] The remaining events are almost entirely $y^0 = \eta$. This is illustrated in Fig. 4, where we plot the distribution in $m^2(y^0)$ for $\pi^+p \to \pi^+py^0$, $y^0 = \pi^+\pi^-x^0$, and where the assignment of the two π^+'s is that which gives $m^2(y^0)$ closest to $m^2(\eta) = 0.300$ $(\mathrm{BeV}/c^2)^2$. The observed width agrees with that expected from PANG measurement errors. The 114 events with $0.28 < m^2(y^0) < 0.32$ $(\mathrm{BeV}/c^2)^2$ give, after corrections, $N(\eta \to \pi^+\pi^-x^0) = 132.6$ "events."

Finally we obtain $\Gamma(\eta \to \gamma\gamma)/\Gamma(\eta \to \pi^+\pi^-x^0) = (5 - 0.33)/(0.0345)(132.6) = 0.99 \pm 0.48$, and $\Gamma(\eta \to 3\pi^0)/\Gamma(\eta \to \pi^+\pi^-x^0) = (12 - 2.50)/(0.105)(132.6) = 0.66 \pm 0.25$.

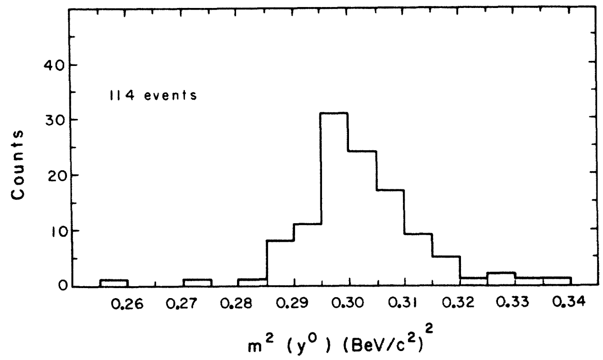

FIG. 4. Distribution in $m^2(y^0)$ for $\pi^+ + p \rightarrow \pi^+ + p + y^0$, $y^0 \rightarrow \pi^+ + \pi^- + x^0$; x^0 = missing neutral.

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[5]The decay $\eta \rightarrow 2\pi^0$ is forbidden for $J^P = 0^-$. The decay $\eta \rightarrow \pi^0 + \gamma$ is forbidden for $J = 0$, and is ruled out experimentally. (See L. Rosenson, reference 4.)

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[10]As long as $m(e^+e^-) \ll m_0$, where $m_0 = 135(\pi^0)$ or $548(\eta^0)$, the relative probability $\Gamma(m_0 \rightarrow \gamma_R e^+e^-)/\Gamma(m_0 \rightarrow 2\gamma_R)$ is insensitive to the mass m_0 (see reference 8). That is why we find 0.0101 for this probability, for both π^0 and η decay, when we have $m(e^+e^-) < 30$ MeV/c^2. For much larger values of $m(e^+e^-)$, the internal conversion probability becomes sensitive to m_0, so that the total internal-conversion probability is larger for $\eta \rightarrow \gamma\gamma$ than for $\pi^0 \rightarrow \gamma\gamma$.

[11]For our criterion $m(e^+e^-) < 30$ MeV/c^2, the γ_V are "almost real," and the distribution in $m^2(x^0)$ for a given $m^2(y^0)$ is expected to be essentially the same for γ_V as for γ_R events. For this reason, and because of the small number of events, we treat both event types together.

[12]We find $\chi^2 = 2.9$, whereas $\langle\chi^2\rangle = 4.0$.

[13]The error is obtained by varying the normalization of the solid histogram until χ^2 (from the first five points) increases by unity. The error 0.6 is the uncertainty in the predicted "average," 4.3, and has nothing to do with the Poisson fluctuations expected.