# THREE-PION MASS DISTRIBUTIONS AND THE $\eta$ MESON*

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Evidence has been reported for two resonances in the $\pi^+\pi^-\pi^0$ system at about 770 Mev ($\omega$)[1-3] and 550 Mev ($\eta$).[2,4] In an investigation of pion production in $p$-$p$ collisions at 2 Bev in the BNL 20-inch hydrogen bubble chamber we observed[5] indications of the $\eta$ in the triple pion production reaction

$$p+p \rightarrow p+p+\pi^+ +\pi^- +\pi^0. \quad (pp+-0)$$

To confirm this, the remainder of the total sample of 1951 four-pronged events in the fiducial volume was measured and analyzed, using the GUTS fitting program and bubble density measurements. 135 $pp+-0$ events, 256 of the type

$$p+p \rightarrow p+n+\pi^+ +\pi^+ +\pi^-, \quad (pn++-)$$

and 1560 of the type

$$p+p \rightarrow p+p+\pi^+ +\pi^-, \quad (pp+-)$$

were obtained.

We report here observation of the charged decay mode of the $\eta$ ($\eta \rightarrow +-0$) in the $pp+-0$ reaction. A search for the $\pi^+\pi^-\gamma$ decay mode ($\eta \rightarrow +-\gamma$) has shown that, if it occurs, the decay rate is very small. Evidence has also been obtained for the decay of $\eta$ into neutrals. There are indications of the $\omega$, and a possible new resonance.

$Q$ values for the $3\pi$ systems, $+-0$ and $++-$, are shown in Fig. 1. The $\eta$ can be seen in the $+-0$ system at an effective mass of $546 \pm 4$ Mev and a width of the order of the experimental resolution. Using known cross sections for $p$-$p$ interactions,[5] we obtain the cross section $\sigma(\eta \rightarrow +-0)$ for

$$p+p \rightarrow p+p+\eta^0, \quad \eta^0 \rightarrow \pi^+ +\pi^- +\pi^0$$

to be $57 \pm 10$ $\mu$b. This corresponds to 35 events

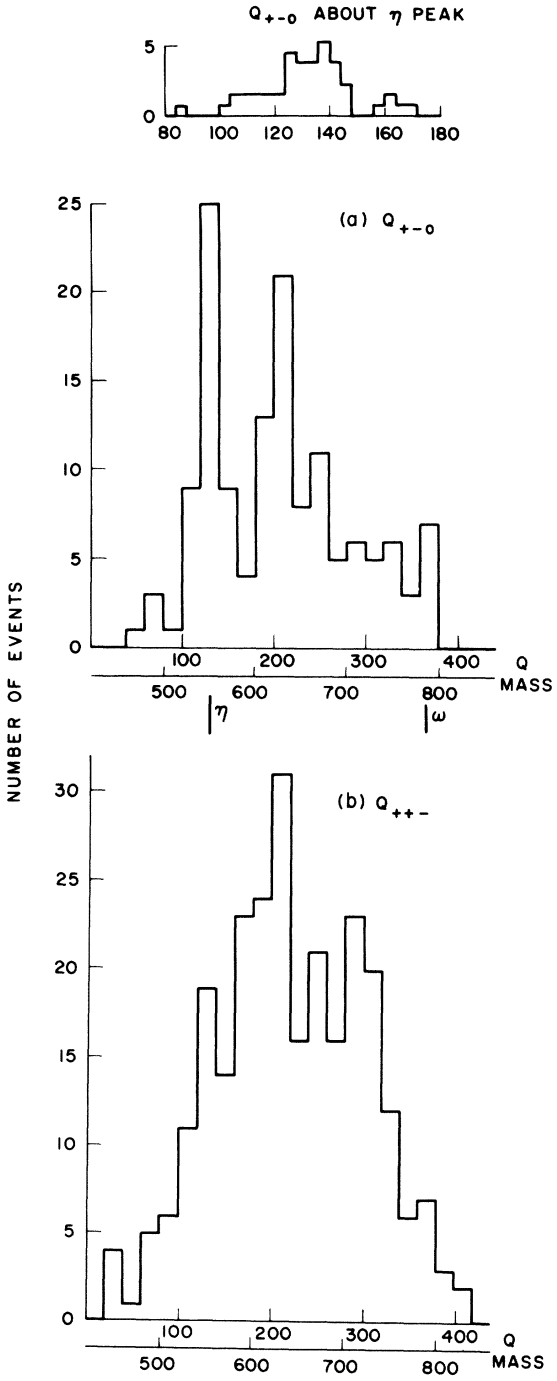


FIG. 1. Histograms of $3\pi$ $Q$ values in 20-Mev intervals: (a) $Q_{+-0}$ from the reaction $p+p \rightarrow p+p+\pi^+ +\pi^- +\pi^0$, (b) $Q_{++-}$ from the reaction $p+p \rightarrow p+n+\pi^+ +\pi^+ +\pi^-$. Effective mass scales are also given. The masses of the $\eta$ and $\omega$ are indicated by vertical lines. The insert above (a) shows $Q_{+-0}$ about the $\eta$ peak, plotted in 4-Mev intervals.

between $Q = 100$ and $Q = 150$ Mev, after subtraction of seven estimated background events. In the ++- system there is an excess of 5 events in the same $Q$ region; this excess is not apparent when the histogram is plotted in 25-Mev intervals. The events are on a rising background and may be assumed to represent a statistical fluctuation. The result is then consistent with assignment of isotopic spin $I = 0$ to the $\eta$.[6]

The main source of background seems to come from excitation of two $N\pi$ isobars in the $\frac{3}{2}, \frac{3}{2}$ state. $Q$ values for the $N\pi$ system were examined. Peaks corresponding to excitation of $p+$ and $n-$ isobars were observed for the $pn++-$ reaction, but there were no corresponding peaks for the $pp+-0$ reaction.[5] This is consistent with the larger background in the $Q_{++-}$ distribution. Because of the low kinetic energy in the center-of-mass system in this experiment, and the width of the $N\pi$ $Q$ values, it is not possible to separate the isobar background events from $\eta$ events.

Dalitz plots, with radial density distributions, are shown in Fig. 2 for three regions of $Q_{+-0}$: $\eta$ ($100 \leq Q < 150$ Mev), the adjacent region ($175 \leq Q < 250$ Mev), and the region ($240 \leq Q < 340$ Mev), which consists mainly of isobar background. The general features of Dalitz plots for $3\pi$ systems have been discussed by Stevenson et al.[7] and Bastien et al.[4] for various spin, parity, and $G$-parity assignments. The $\eta$ Dalitz plot shows a possible depletion of events at large $T_0$, although this effect is not so marked as that observed by Bastien et al. With the small total number of events available, the effect may be a statistical fluctuation. The radial density [Fig. 3(d)] is uniform, which disagrees with predicted distributions for an $I = 0$, $G = -1$ state. $J = 0^-$ and $1^+$ give zero density at the center and maximum at the boundary; $1^-$ gives maximum density at the center and zero at the boundary. For $G = +1$, $0^-$ gives a uniform distribution, $1^+$ gives a high density of events at large $T_0$, and $1^-$ gives zero density at the boundary and along the $T_0$ axis. The experimental distribution is consistent with $0^{-+}$ within the limited statistics, similar to the conclusions of Bastien et al. It is necessary to assume that the $3\pi$-decay modes (forbidden for $G = +1$) occur through virtual electromagnetic transitions.

The neutral decay modes expected for $\eta$ would be $2\gamma$ and $3\pi^0$, with the branching ratio $(000)/(+-0) \leq \frac{3}{2}$. To investigate neutral modes we looked at the missing-mass distribution for $p$-$p$ two-pronged events[8] which did not fit either the elastic scattering or single pion production. Figure 3(a) shows

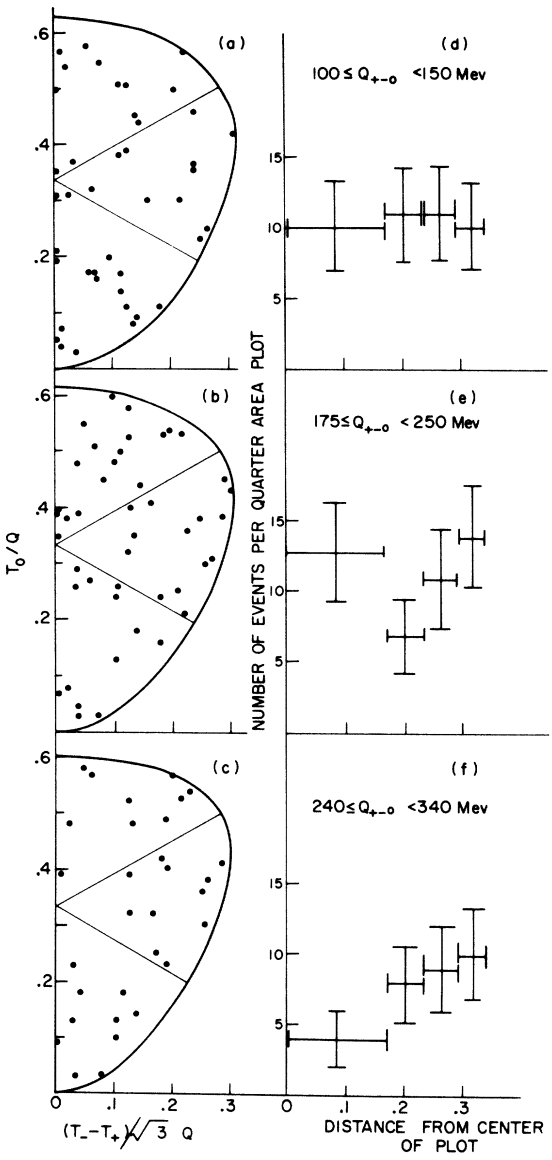


FIG. 2. Dalitz plots (folded about $T_0$ axis) with corresponding radial density distributions for three regions of $Q_{+-0}$. $T_0$, $T_+$, and $T_-$ are the kinetic energies of the three pions in their rest frame.

this distribution. The corresponding effective-mass curve for events with two charged pions ($pp+-$) falls fairly smoothly from about 450 Mev.[5] Assuming a similar background from $\pi^0\pi^0$ events, we have attributed the peak between 500 and 550 Mev to the $\eta$ neutral decay mode in

$$p + p \rightarrow p + p + \eta^0 \rightarrow \text{neutrals.}$$

An estimate of ten events above background

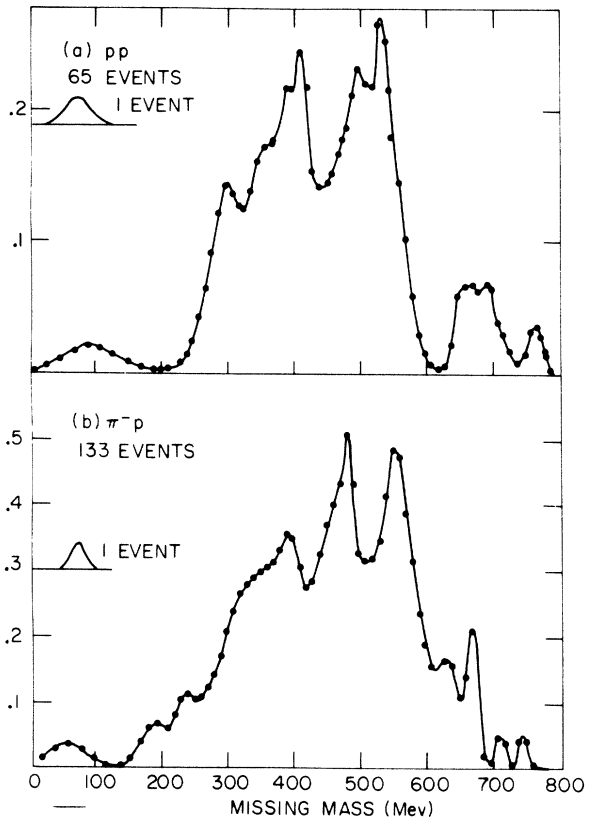


FIG. 3. Gaussian ideograms for missing-mass values from the reactions: (a) $p+p \rightarrow p+p+$ neutrals, and (b) $\pi^-+p \rightarrow \pi^-+p+$ neutrals. Events which fitted elastic scattering or single pion production are not included.

gives a cross section $\sigma(\eta \rightarrow \text{neutrals}) = 140 \pm 55$ $\mu$b. Thus the branching ratio $(\eta \rightarrow \text{neutrals})/(\eta \rightarrow +-0)$ is $(140 \pm 55)/(57 \pm 10) = 2.5 \pm 1.0$.

The corresponding missing-mass distribution obtained in $\pi^-p$ interactions at 1.25 Bev, shown in Fig. 3(b), is similar to the $p$-$p$ distribution. There is a peak at 550 Mev, which we assume to be due to

$$\pi^- + p \rightarrow \pi^- + p + \eta^0 \searrow \text{neutrals}.$$

After an estimation of background, the cross section obtained, corresponding to this peak, is $83 \pm 25$ $\mu$b. An estimation of the cross section for the production of $\eta$, and its subsequent decay by the charged mode in

$$\pi^- + p \rightarrow \pi^- + p + \eta^0 \quad (p-+-0)$$
$$\eta^0 \searrow \pi^+ + \pi^- + \pi^0,$$

was also made, based on observing five events corresponding to $\eta$ out of a total observed sample of 15 $p$-+-0 events. Thus the value $20 \pm 9$ $\mu$b was found, giving a branching ratio $(\eta \rightarrow \text{neutrals})/(\eta \rightarrow +-0)$ of $4.2 \pm 1.5$, in approximate agreement with the value obtained in $p$-$p$ interactions. With the present statistics and uncertainties in background estimates, the branching ratio might not be greater than $\frac{3}{2}$, and 000 could be the dominant neutral decay mode.

Since the $3\pi$-decay modes ($G$ forbidden with the assignment $0^{-+}$) could only occur through electromagnetic transitions, an alternative mode,

$$\eta \rightarrow \pi^+ + \pi^- + \gamma,$$

should be relatively abundant. All our events with two protons (1560 $pp$+- and 135 $pp$+-0) were tested for the hypothesis

$$p + p \rightarrow p + p + \pi^+ + \pi^- + \gamma. \quad (pp+-\gamma)$$

As would be expected, the measuring errors permit a large proportion of the events to fit this hypothesis with a low-energy $\gamma$ ray. The c.m. energy distribution of the $\gamma$'s indicated that $\gamma$'s below 50 Mev come from fictitious fits. 75 $pp$+- events fitted $pp$+-$\gamma$ with $\chi^2 < 5$ and $E_\gamma > 50$ Mev. A plot of $Q_{+-\gamma}$ showed an excess of three events in the expected interval over a smooth background of five events per 20-Mev interval, equivalent to a cross section $5 \pm 5$ $\mu$b. A selection with $E_\gamma > 80$ Mev gave no events in the expected interval. There is also no $\eta$ peak for events with $E_\gamma < 50$ Mev.

106 $pp$+-0 events fitted $pp$+-$\gamma$ with $\chi^2 < 5$. However, the missing-mass distribution shows a sharp peak about the $\pi^0$ mass, with a full width at half maximum of approximately 40 Mev. 20 events in the tail are consistent with zero mass. Neither the total sample of 106 events nor these 20 events showed peaking at the $\eta$ mass in the $Q_{+-\gamma}$ plot. Thus we consider the cross section 5 $\mu$b to be an upper limit for the +-$\gamma$ decay mode in the $pp$+-$\gamma$ reaction, so that the branching ratio $(\eta \rightarrow +-\gamma)/(\eta \rightarrow +-0) < 9\%$ (5 $\mu$b/55 $\mu$b). A similar result was obtained by Bastien et al.[4] in $Kp$ interactions. This result seems difficult to reconcile with the assignment $G = +1$ to the $\eta$.

There is a peak in both +-0 and ++- $Q$ distributions (Fig. 1) at about 210 Mev (mass ~ 625 Mev). If this corresponds to another resonance, its isotopic spin must be $I = 1$ or 2. We estimate the cross sections corresponding to events in the peaks to be $32 \pm 7$ $\mu$b for the +-0 systems and $48 \pm 9$ $\mu$b for the ++- system, assuming a smooth background for each distribution. The Dalitz plot for the +-0 system in the region of this peak [Fig.

2(b)] is approximately uniform, although there may be a depletion of events at low $T_0$.

It has been suggested[9] that there may exist a $1^{+-}$, $I=1$ meson, called $\alpha$, which might determine the structure of the axial vector strangeness-nonchanging form factor of the weak decays, $F_A(q^2)$, at low energies. Dennery and Primakoff[9] have estimated that $m_\alpha \simeq m_\rho/1.2 = 4.3 m_\pi$, a value which is not inconsistent with the second mass peak in Fig. 1. The only purely neutral decay mode (into known particles) of such an object would be a decay into three $\pi^0$ mesons.[10] For the 000 and +-0 decay modes the branching ratio would be $(000)/(+-0) \leq \frac{3}{2}$, which would be consistent with the observation of very few events above 600 Mev in the missing-mass distribution in Fig. 3.

It should be emphasized that our statistics are limited. If we are observing a true resonance and not, for example, a final-state interaction peculiar to the $p$-$p$ system, the peaks should be seen in other processes. So far, experiments in which $\eta$ or $\omega$ have been found have not shown striking peaks in this energy region. The cross section for production appears to be small, and the c.m. energies of other experiments may have been less suitable.

We wish to thank the BNL bubble chamber group and our scanners for their invaluable services. We are indebted to Dr. W. J. Fickinger for providing data from his sample of two-pronged $p$-$p$ events. We thank Dr. J. Bernstein for helpful discussions.

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[10]The decay $\alpha^0 \rightarrow 2\gamma$ is forbidden by angular momentum conservation and $\alpha^0 \rightarrow 2\pi^0$ by Bose statistics, while $\alpha^0 \rightarrow \gamma + n\pi^0$ is forbidden by charge conjugation invariance.

## $\Lambda^0$-$K^0$ PRODUCTION BY PIONS ON PROTONS*

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The associated production of hyperons and heavy mesons in pion-proton collisions was first observed in the Brookhaven National Laboratory diffusion cloud chamber.[1] Since then the production of strange particles in the same and similar reactions has been studied by many groups.[2] This Letter is concerned with the extension of this work to lower energies, specifically incident pion kinetic energies of 775, 791, 829, and 871 Mev. The pion interactions were observed in the BNL 20-in. hydrogen bubble chamber. Since the primary pion energies are above the $\Lambda K$ threshold but below that for $\Sigma K$ production, only one strange particle channel is available, namely,

$$\pi^- + p \rightarrow \Lambda^0 + K^0, \quad K^0 \rightarrow \pi^- + \pi^+, \quad \Lambda^0 \rightarrow \pi^- + p \quad . \tag{1}$$

We report here the cross sections, angular distributions, and polarizations of the $\Lambda^0$ for the above reaction as a function of energy.

The external proton beam at the Cosmotron was caused to strike a 6-in. Cu target. Negative pions which emerged at an angle of 4° were subsequently focussed and bent through 45° by a