DECAY MODES AND WIDTH OF THE η MESON*

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In a study of multipion final states produced by 1.23-Bev/c π^+ interactions in deuterium, Pevsner et al. have reported that, in addition to a peaking in the mass distribution for neutral three-pion systems at $M = 764$ Mev observed previously in antiproton annihilations, a marked peaking occurs at $M = 546$ Mev with a full width at half-maximum $\Gamma < 25$ Mev.[1] This latter peaking has been interpreted by them as evidence for the decay, via strong interactions, of an unstable particle, the η meson, into a three-pion state whose isotopic spin, angular momentum, and parity remain undetermined.

The threshold for η production by K^- mesons on protons,

$$K^- + p \to \Lambda + \eta^0, \qquad (1)$$

is at a K^- momentum of 725 Mev/c. Reaction (1) with subsequent three-pion decay of η^0 via the charged mode, $\eta_{ch}{}^0$, produces the final state,

$$K^- + p \to \Lambda + \pi^+ + \pi^- + \pi^0, \qquad (2)$$

while a neutral decay, $\eta_{neut}{}^0$, yields

$$K^- + p \to \Lambda + \text{neutrals}. \qquad (3)$$

We have observed a total of 606 events of the topology of types (2) and (3) produced by 760- and 850-Mev/c K^- mesons in the Lawrence Radiation Laboratory 15-in. hydrogen bubble chamber. On the basis of the mass distributions shown in Figs. 1 and 2, we conclude that η^0 production is involved in both reactions (2) and (3). As indicated in the summary given in Table I, we find the cross section for η^0 production at 760 Mev/c to be (0.63 ± 0.11) mb, and yet, disconcertingly, at 850 Mev/c $\sigma(\eta^0)$ appears to be $\lesssim 0.04$ mb. The branching ratio $\eta_{ch}{}^0/\eta_{neut}{}^0$ at 760 Mev/c is 0.31 ± 0.11.

Figure 1 and Fig. 2 (bottom) are histograms of the mass of the neutrals in reaction (3). Figure 2 (top) shows a histogram of the effective mass $M_{3\pi}$ of the three pions in reaction (2). Using the errors calculated by the fitting program KICK, we have obtained the resolution of our system from a resolution function generated in a manner described in detail by Maglić et al.[2] We have further calibrated our errors by using the reaction,

$$K^- + p \to \bar{K}^0 + n, \qquad (4)$$

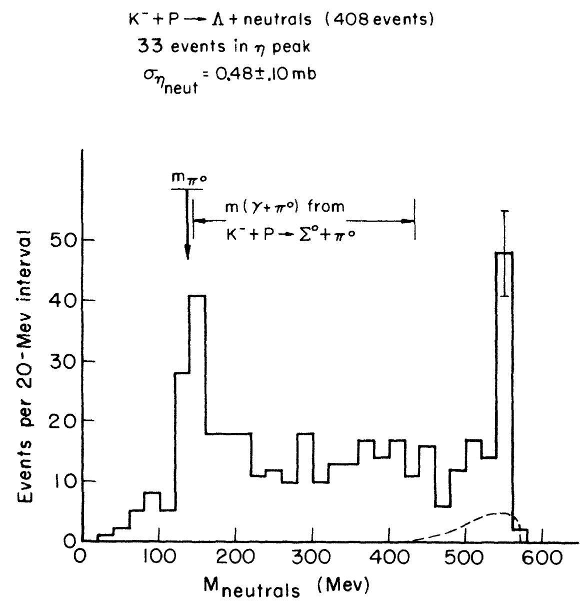

FIG. 1. Missing-mass spectrum for 408 events corresponding to reaction (3), at $P_{K^-} = 760$ Mev/c. The peak to the left corresponds to the final state $\Lambda\pi^0$. Most of the events to the right of the π^0 peak and below a mass of 434 Mev correspond to $\Sigma^0\pi^0$ production where $\Sigma^0 \to \Lambda + \gamma$. In the peak to the right 33 events have been attributed to η's (see Fig. 2, bottom). The other possible final states are $\Sigma^0\pi^0\pi^0$, $\Lambda\pi^0\pi^0$, and $\Lambda\pi^0\pi^0\pi^0$. The dashed curve represents the phase space allowable by charge independence for $\Lambda 3\pi^0$. [If we assume that all our $\Lambda\pi^+\pi^-\pi^0$ are background events (i.e., no η production), then charge independence requires $\sigma(\Lambda\pi^+\pi^-\pi^0)/\sigma(\Lambda\pi^0\pi^0\pi^0) > \frac{2}{3}$.] Phase space for $\Lambda\pi^0\pi^0$ starts at $2\pi^0$, and phase space for $\Sigma\pi^0\pi^0$ at 285 Mev. It should be noted that the maximum cross section for $\Lambda\pi^0\pi^0$ is about 0.35 mb; i.e., we know that the ratio $\sigma(K^-p \to \Lambda\pi^0\pi^0)/\sigma(K^-p \to \Lambda\pi^+\pi^-) = 1.4$ from K^- in deuterium at 760 Mev/c [D. J. Prowse et al., University of California at Los Angeles (private communication)]. We know further that $\sigma(K^-p \to \Lambda\pi^+\pi^-) = 2.9$ mb from K^- in hydrogen at 760 Mev/c. Using these facts and charge independence, one gets a maximum cross section for $\Lambda\pi^0\pi^0$ of about 0.35 mb.

to calculate the mass of the neutron and its error. The central values were obtained by plotting Gaussian ideograms. The results are summarized in Table II. Considering the uncertainties in our experimental widths, we estimate an upper limit of

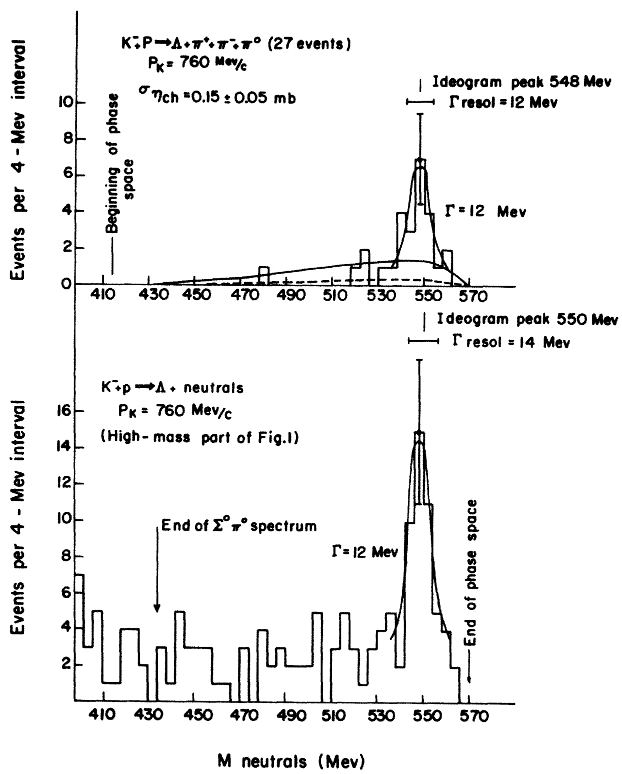

FIG. 2. (Top): The $M_{3\pi}$ spectrum from reaction (2). The solid curve is Lorentz-invariant phase space normalized to the 27 $\Lambda\pi^+\pi^-\pi^0$ events. Such a curve predicts 14 events below 530 Mev which are not there. Consequently another dashed curve has been drawn normalized to the four events to the left of 530 Mev. This implies that there are three background events above 530 Mev. It should be remarked further that the cross section for $K^-p \to \Lambda\pi^+\pi^-\pi^0$ at 760 Mev/c is about zero [D. Prowse, UCLA (private communication)], meaning that the $\Lambda\,3\pi$ channel seems to be $I=0$ at that momentum. Therefore there should not be any $K^-p \to Y_0^{**0}\pi^0$ final state present at 760 Mev/c. (Bottom): The high-energy part of Fig. 1. The fact that the width of the resolution function is larger than the histogram width can be attributed to a statistical fluctuation or a slight misassignment of our errors.

$\Gamma = 7$ Mev on the width.

It is of interest to determine the extent to which our data may be used to constrain the assignment of possible spin-parity states to the η. We assume that the η has $I=0$,[3] and consider two cases, charge conjugation $C=-1$ and $+1$. Since the G parity of a neutral meson obeys the rule $G=C(-1)^I$, then for $I=0$, we have $G=C$. For $G=C=-1$, decay into $\pi^+\pi^-\pi^0$ represents an allowed transition. However, the complete spatial antisymmetry of the $I=0$ three-pion state (a) forbids decay into $\pi^0\pi^0\pi^0$ and (b) ensures sixfold symmetry for the density of points on a Dalitz plot. Though this latter condition is not well satisfied by our data (see Fig. 3), we may tentatively assume that the deviations represent a statistical fluctuation, and examine the consistency of the data with the simplest spin, parity, and G-parity assignments for the three-pion system: 0^{--}, 1^{--}, 1^{+-}. The general behavior of these spatial states has been discussed by Maglić et al.[2] In particular, the matrix element for the 1^{--} state must vanish at the boundary of the Dalitz plot, while for the 0^{--} and 1^{+-} states, its value must tend to zero in the center of the Dalitz plot. Though of limited statistical significance, our data do not favor any of these hypotheses.[4,5]

If C and G for the η are $+1$, decay into two or four pions might be expected but has not been observed. Four-pion decays may be absent because the Q value in that case is approximately zero. For $J \leq 1$, there are four spin and parity assignments: 0^+, 0^-, 1^+, 1^-. The first, 0^+, would decay strongly into 2π; the last three cannot. Decay into three pions may still occur, but only via virtual electromagnetic transitions, which change G to -1 and I to 1.[6] With $I=1$, decay into $\pi^0\pi^0\pi^0$ is possible with the branching ratio $\Gamma(\pi^0\pi^0\pi^0)/\Gamma(\pi^+\pi^-\pi^0) \leq \frac{3}{2}$. The measured branching ratio, $\eta_{\rm neut}/\eta_{\rm ch} \approx 3$, leads to the conclusion that radia-

Table I. Production of η mesons and background.[a]

	760 Mev/c		850 Mev/c	
	σ (mb)	Events	σ (mb)	Events
$\sigma(\Lambda+\text{neutrals})$	6.0 ± 0.4	408	4.1 ± 0.4	148
$\sigma(\eta_{\rm neut}{}^0)$	0.48 ± 0.10	33	$<0.02 \pm 0.02$	≤ 1
$\sigma(\Lambda\pi^+\pi^-\pi^0)$	0.20 ± 0.05	27	0.15 ± 0.05	23
$\sigma(\eta_{\rm ch}{}^0)$	0.15 ± 0.05	20	$<0.02 \pm 0.02$	<3
$E(\text{c.m.}) - (m_\Lambda + m_\eta)$	20 Mev[b]		63 Mev	

[a]The path lengths scanned for reactions (2) and (3) were in the ratio of 1.64/1.0.
[b]This row is the Q value for $\Lambda+\eta$ production.

Table II. Calculations of masses and widths.[a]

	$\Gamma_{\text{resolution}}$ (Mev)	$\Gamma_{\text{histogram}}$ (Mev)	Central value of ideogram (Mev)
η_{neut}^0 in reaction (4)	14	12	550 ± 1.5
η_{ch}^0 in reaction (3)	12	12	548 ± 2.0
Neutron in $K^- + p \to \bar{K}^0 + n$	20	22	941 ± 1.0

[a]$\Gamma_{\text{histogram}}$ is the full width of our experimental histogram. $\Gamma_{\text{resolution}}$ is the width we would expect if the true peak were a line (reference 2).

Table III. The G-forbidden 3π decays.[a]

Meson	l,L	Simplest matrix element[b]	Vanishes at	Dominant radiative decay modes
0^{-+}	0,0	α	nowhere	2γ, $\pi^+\pi^-\gamma$
1^{++}	1,0	$\alpha\vec{p}$	$T_{\pi^0} = 0$	$\pi^+\pi^-\gamma$
1^{-+}	2,2	$\alpha(\vec{p}\times\vec{q})(\vec{p}\cdot\vec{q})$	T_{π^0} axis and boundary	$\pi^+\pi^-\gamma$

[a]The matrix element is analyzed in terms of a $\pi^+\pi^-$ pair and a π^0. The $\pi^+\pi^-$ pair is assigned momentum $\vec{q}$ and angular momentum $\vec{L}$. The remaining π^0 is described in the 3π rest frame by momentum $\vec{p}$ and angular momentum $\vec{l}$.

[b]The factor α (fine-structure constant) appears since G-forbidden transitions require that the decay proceed via electromagnetic interaction.

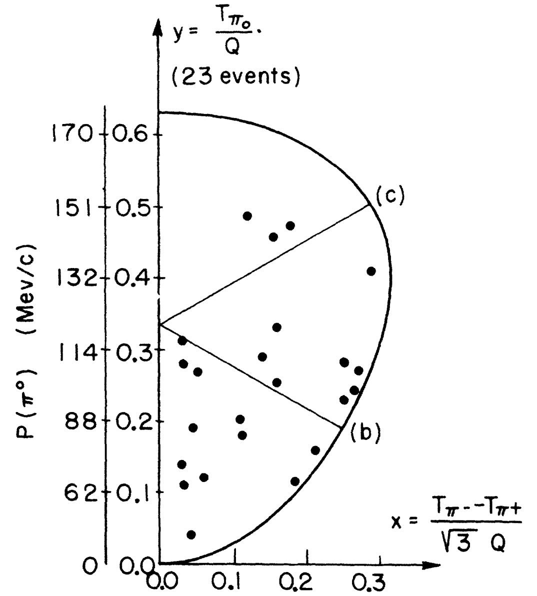

FIG. 3. Normalized Dalitz plot for 23 of the 27 events of Fig. 2 (top). The four events with $M_{3\pi} < 530$ Mev were interpreted as background and excluded. As shown in Fig. 2 (top), three or four of the remaining events are probably also background. Charge-conjugation invariance allows us to fold the plot about the T_{π^0} axis. For $G = -1$, the plot can be folded again about the T_{π^+} and T_{π^-} axes (b) and (c). No control-region plot is presented, since we have only four events clearly outside the η_{ch}^0 peak.

tive decays must be present. Since the decay reactions are invariant under charge conjugation, the neutral decay mode $\eta \to \gamma +$ any number of π^0 is forbidden, while $\eta \to \pi^+ + \pi^- + \gamma$ and $\eta \to \gamma + \gamma$ (the latter only for 0^{-+}) are allowed. We have systematically examined all events leading to $\Lambda\pi^+\pi^-$ in the final state for consistency with the hypothesis $K^- + p \to \Lambda + \eta$ followed by $\eta \to \pi^+ + \pi^- + \gamma$, with a negative result. We conclude that $\Gamma(\pi^+\pi^-\gamma)/\Gamma(\pi^+\pi^-\pi^0) < \frac{1}{20}$ and, if the η is 0^{-+}, $\Gamma(\pi^+\pi^-\gamma)/\Gamma(\gamma\gamma) < \frac{1}{10}$.[7] It is unexpected, but not impossible, that these two radiative modes are as slow as these G-forbidden 3π modes.

Table III lists the simplest forms of the matrix elements for the three cases under consideration. The simplest matrix element for the case 0^{-+} is a constant. We see from Fig. 3 that the Dalitz plot is not uniform, but rather favors low-energy T_{π^0}. However, this result could still be consistent with a 0^{-+} meson. That is, the population of the Dalitz plot in the simplest case of a forbidden three-pion decay could be nonuniform for various reasons; for example, as a result of strong final-state interactions or because of the effects of electromagnetic interactions in the decay process itself (for example, if the three pions are formed between the emission and absorption of the virtual photon, then the reabsorption of the photon would distinguish between charged and neutral pions).

The simplest matrix element for the case 1^{-+} requires that the population of the Dalitz plot tend to zero along the T_{π^0} axis and the boundary. Similarly, for the case 1^{++} one would expect a vanishing population at $T_{\pi^0}=0$. Again with limited statistical significance, the Dalitz plot in Fig. 3 does not favor either of these possibilities.[8]

We conclude that our results are most consistent with the quantum numbers 0^{-+} for the η (these are the same as the quantum numbers of the χ meson introduced in the "eightfold way" of Gell-Mann[9]). Statistical limitations and background do not permit us to rule out the case 1^{--} with certainty.

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[1]A. Pevsner, R. Kraemer, M. Nussbaum, C. Richardson, P. Schlein, R. Strand, T. Toohig, M. Block, A. Engler, R. Gessaroli, and C. Meltzer, Phys. Rev. Letters 7, 421 (1961).

[2]B. C. Maglić, L. W. Alvarez, A. H. Rosenfeld, and M. L. Stevenson, Phys. Rev. Letters 7, 178 (1961); M. L. Stevenson, L. W. Alvarez, B. C. Maglić, and A. H. Rosenfeld, Phys. Rev. 125, 647 (1962).

[3]D. D. Carmony, A. H. Rosenfeld, and R. T. Van de Walle, following Letter [Phys. Rev. Letters 8, 117 (1962)]; also D. Prowse, University of California at Los Angeles (private communication).

[4]The authors of reference 1 inform us that, within their equally limited statistics, their Dalitz plot is consistent with 1^{--}.

[5]If η is 1^{--} (like ω) then the following comparison suggests that its width should indeed be much less than our 7-Mev upper limit. It is known that $\Gamma_\omega < 24$ Mev, and $\Gamma \propto |E_1P_2P_3|^2Q^2$ [the matrix element M is proportional to $E_1(\vec{P}_2\times\vec{P}_3)$ and the area of the Dalitz plot varies as $Q^2=(m_\omega - m_{3\pi})^2$] which drops by a factor of ~100 when we substitute $m_\eta=550$ Mev instead of $m_\omega=780$ Mev. Thus we expect a partial width $\Gamma < 0.24$ Mev. Presumably the dominant decay rate is $\Gamma(\eta^0\rightarrow\pi^0+\gamma)$, which has been estimated at 0.03 Mev [see J. J. Sakurai, Phys. Rev. Letters 1, 355 (1961)], in which case $\Gamma(\eta_{ch}^0)$ is about 0.01 Mev.

[6]The 3π final state must have $G=-1$, but C must still be +1. By the rule $G=C(-1)^I$ for neutral particles, I must then have changed to an odd number. We assume emission and absorption of a single photon ($\Delta I \leq 1$ for each process), so $I=0$ can lead only to $I=1$. This analysis is equivalent to that of H.-P. Duerr and W. Heisenberg, "Quantum Numbers of the ω Meson" (Max-Planck-Institut für Physik und Astrophysik, München, Germany; unpublished work).

[7]M. Gell-Mann [California Institute of Technology, Pasadena, California (private communication)] has estimated $\Gamma(\gamma\gamma)/\Gamma(\gamma\pi^+\pi^-)\approx 4$, not inconsistent with our data.

[8]Another argument against 1^{-+} and 1^{++} is that they have no way to decay copiously into neutrals. $\Gamma(\pi^0\pi^0\pi^0)/\Gamma(\pi^+\pi^-\pi^0)$ must be $\ll 1$, and $\gamma+\pi^0$, $\gamma+n\pi^0$, and $\gamma+\gamma$ are all forbidden.

[9]M. Gell-Mann, California Institute of Technology Scientific Laboratory Report CT-SL-20 (unpublished).

EVIDENCE THAT THE η MESON HAS ISOSPIN ZERO*

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Pevsner et al. have reported the existence of the η meson (mass 550 Mev) produced by 1.23-Bev/c positive pions on neutron targets in deuterium[1]:

$$\pi^+ + n(+p) \rightarrow p(+p) + \eta^0. \quad (1)$$

The η^0 then decays by its charged mode:

$$\eta_{ch}^0 \rightarrow \pi^+ + \pi^- + \pi^0 + 135 \text{ Mev}. \quad (2)$$

The η is also produced by[2]

$$K^- + p \rightarrow \Lambda + \eta^0. \quad (3)$$

It is observed that the η^0 has a width $\Gamma \leq 15$ Mev and a neutral decay mode, which in fact is the dominant branching fraction. This is, the charged branching fraction f_{ch}^0 is less than $\frac{1}{3}$, where $f_{ch}^0 \equiv (\eta^0\rightarrow\pi^+\pi^-\pi^0)/(\text{all modes})$. As discussed by Bastien et al., this means that radiative modes must be present in η^0 decay.[2] From reaction (3), we see that η can have only isospin 0 or 1. The purpose of this Letter is to rule out $I=1$.

Using the impulse approximation, the Hulthén wave function for the deuteron, and the experi-