DECAY MODES AND PROPERTIES OF THE X^0†

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In two recent Letters,[1,2] evidence was presented for the existence of the "X^0," a meson of strangeness 0, mass 960 MeV, and narrow width. In this note we discuss the evidence pertinent to the detailed nature of the X^0 decay modes and quantum number assignments including G-parity, isospin, spin, and parity.

In reference 1 we reported observation of three final states of X^0 decay, namely (A) $X^0 \to$ neutrals, (B) $X^0 \to \pi^+ + \pi^+ + \pi^- + \pi^- + \pi^0$, (C) $X^0 \to \pi^+ + \pi^- +$ neutrals, which occur[1,2] in the ratio ~4:1:4. The detailed nature of these final states is discussed below.

The mode (B) can be ascribed to either of two decay chains:

$$X^0 \to 5\pi \text{ (direct)}$$

or

$$X^0 \to \eta^0 + \pi^+ + \pi^-$$
$$\quad \llcorner \pi^+ + \pi^- + \pi^0.$$

Direct evidence against $X^0 \to 5\pi$ comes from considerations based on the distribution of the four possible $(\pi^+\pi^-\pi^0)$ mass combinations for each 5-pion final state. The outstanding feature of the distribution is that every one of the 45 X^0 events[3] contains at least one $M(\pi^+\pi^-\pi^0)$ combination consistent with the η^0 mass (taken to be 550 ± 25 MeV for these well-measured events). It is easy to see that this circumstance is inconsistent with the assumption $X^0 \to 5\pi$. Firstly we estimate from the appropriate 3π phase space the probability P_η that three pions from $960 \to 5\pi$ have $M(3\pi) = 550 \pm 25$ MeV. Including resolution broadening, we find $P_\eta = 0.2 \pm 0.05$. Then, ignoring correlations[4] among the four possible mass choices, the expected number of events with at least one "successful" mass combination is only $45[1-(1-0.2 \pm 0.05)^4] \approx 27 \pm 3$ events which is $(45-27)/3 \approx 6$ standard deviations from the observed value. A study of the entire distribution of observed $M(3\pi)$ favors $X^0 \to \eta^0 + \pi^+ + \pi^-$ by 10 standard deviations, so we shall ignore the 5π possibility from here on.

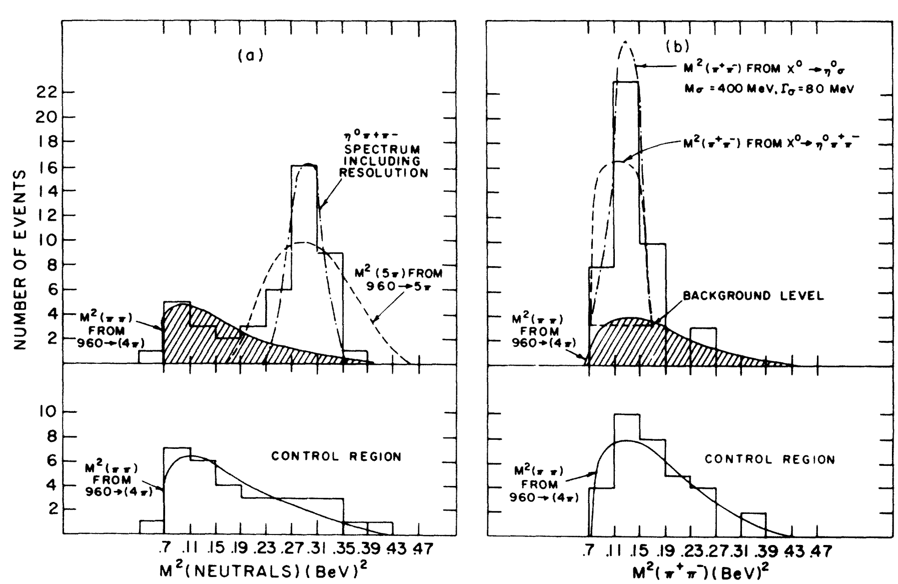

FIG. 1. (a) The mass subspectrum, M^2(neutrals) from "960" $\to \pi^+ + \pi^- +$ neutrals (peripheral) events and control events. (b) The mass subspectrum $M^2(\pi^+\pi^-)$ from "960" $\to \pi^+ + \pi^- +$ neutral (peripheral) events and control events. The "960" spectra are compared with expectations from the possibilities $X^0 \to \eta^0 + \pi^+ + \pi^-$ and $X^0 \to \eta^0 + \sigma$.

Turning now to an examination of the final state (C), we have two possible contributing $\eta^0\pi\pi$ modes:

$$X^0 \to \eta^0 + \pi^+ + \pi^- \quad \llcorner \text{neutrals } (70\,\%) \qquad (\alpha)$$

and/or

$$X^0 \to \eta^0 + \pi^0 + \pi^0 \quad \llcorner\, \pi^+ + \pi^- + \pi^0 \; (24\,\%). \qquad (\beta)$$

Assuming the X^0 decay to be strong, only the first of these possibilities is allowed for $I=1$, while both are allowed for $I=0$ with a ratio[5] $(\beta)/(\alpha) \approx \frac{1}{6}$. Both the M^2(neutrals) and $M^2(\pi^+\pi^-)$ spectra from (C) are shown in Figs. 1(a) and 1(b) and compared with suitable control spectra.[1] The control spectra are consistent with 2π phase space from the background $\Lambda 4\pi$ reaction. The 960 spectra are consistent with a 30% contamination of this background, as determined in reference 1. The neutrals spectrum exhibits a strong η^0 contribution; the data are consistent[6] with either (α) alone or $(\alpha)/(\beta) \approx 6/1$. In the $\pi^+\pi^-$ spectrum there is some indication of a possible "σ enhancement"[7] of the type suggested[8] to explain final-state interactions in τ and η decay; but no strong conclusion can be drawn.

In addition to the modes (A), (B), and (C), we have searched for 2π, 3π, and 4π decay modes in the final states $\Lambda^0(\Sigma^0)2\pi$, $\Lambda^0 3\pi$, and $\Lambda^0 4\pi$, respectively. No evidence for any of these modes was found. From all available data we can set an upper limit of $\approx$15% to the relative rates $n\pi/[(\mathrm{A})+(\mathrm{B})+(\mathrm{C})]$. In order to search for a possible $\pi^+\pi^-\gamma$ decay mode of the X^0, we studied a select subgroup of the reactions

$$\Lambda^0\pi^+\pi^-,\ \Sigma^0\pi^+\pi^-,\ \text{and}\ \Lambda^0\pi^+\pi^-\pi^0, \qquad (1)$$

where kinematic fitting gives no unique identity on the basis of χ^2; i.e., the event is consistent with either the last two, or all three of the reactions (1). The $(\mathrm{MM})^2$ spectrum of 399 such candidates analyzed as "Λ + missing mass (MM)" is shown in Fig. 2. Aside from the ω^0 peak due to the $\Lambda\pi^+\pi^-\pi^0$ contribution, one sees an enhancement at 960 MeV containing 24^{+5}_{-10} events. On the basis of our selection criteria these events might be interpreted either as $X^0 \to \pi^+ + \pi^- + \pi^0$ or $X^0 \to \pi^+ + \pi^- + \gamma$ (for simplicity, we ignore a possible small contribution for $X^0 \to \pi^+ + \pi^- + \pi^0 + \gamma$). However, the absence of any indication of a three-pion mode in our study of the unique $\Lambda\pi^+\pi^-\pi^0$ sample rules out the first possibility. We conclude that these events are due to $X^0 \to \pi^+ + \pi^- + \gamma$. [Observation of 114 ± 33 X^0 events corresponds to $\sigma(K^- + p \to X^0 + \Lambda) = 100 \pm 29$ μb.]

We shall now consider possible quantum number assignments of the X^0, starting with the G-parity. Let us first assume that G is +1. With this assumption, the $\eta^0\pi^+\pi^-$ decay is G-allowed.[9] Also the 3π mode is forbidden[10] and, in fact, all observed decay rates are in agreement with estimates based upon phase space and the known η^0 decay rates (see Table I). On the other hand, if we assume $G = -1$, the 3π mode is G-allowed for all permissible J^P values, and its expected dominance is in significant disagreement with the observed upper limit to its relative rate. Similarly, with $G = -1$, $\eta\pi\pi$ decay is G-forbidden occurring electromagnetically with a rate $\approx\alpha^2$, while $\pi^+\pi^-\gamma$ decay is allowed with a rate $\approx\alpha$. Ignoring barriers, we estimate[11] $(X_0 \to \pi^+ + \pi^- + \gamma)/(X^0 \to \eta + \pi + \pi) \approx 10^3$. This predominance persists[10] even if we assume two-body phase space corresponding to a "σ enhancement" for the denominator and none for the numerator ($X^0 \to \sigma + \gamma$ is forbidden for $J=0$). Since the observed $\pi^+\pi^-\gamma/\eta\pi\pi$ ratio is $\lesssim \frac{1}{5}$, we conclude that the $X^0 \to \eta + \pi + \pi$ decay is strong, i.e., that $G = +1$.

To investigate possible I, J^P assignments, we turn now to an analysis of the Dalitz plot data

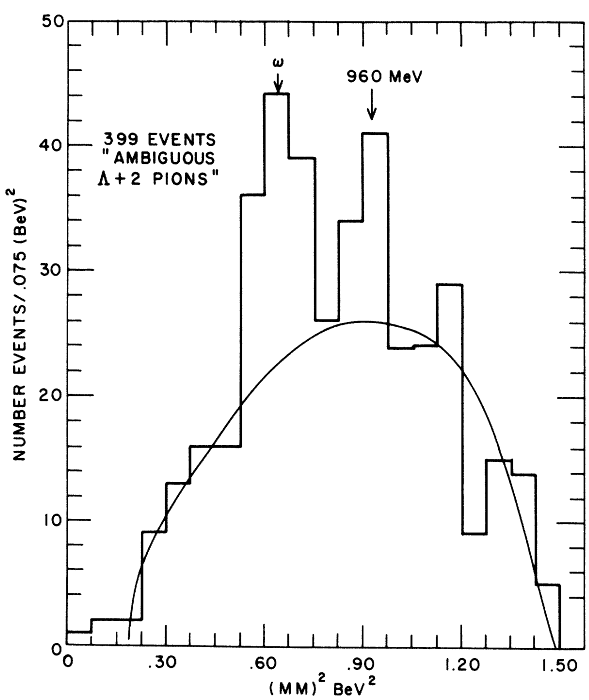

FIG. 2. Missing mass (MM) spectrum from "ambiguous $\Lambda + 2\pi$" events treated as Λ+MM events (see text).

Table I. X^0 decay modes. X^0 decay final state.

	$\pi^+\pi^-\pi^+\pi^-\pi^0$ (B)		$\pi^+\pi^-$ neutrals (C)		All neutrals (A)		$\pi^+\pi^-\gamma$	
I, J^{PG}	Decay chain	Expected rate	Decay chain	Expected rate	Decay chain	Expected rate	Decay chain	Expected rate
$0, 0^{-+}$	$\eta^0\pi^+\pi^-$ └→ $\pi^+ + \pi^- + \pi^0$	0.16	$\eta^0\pi^0\pi^0$ └→ $\pi^+ + \pi^- + \pi^0$ and $\eta^0\pi^+\pi^-$ └→ neutrals	0.56	$\eta^0\pi^0\pi^0$ └→ neutrals $\gamma\gamma$	0.24 ~small	direct	$\sim\frac{1}{4}$
$1, 1^{++}$	$\eta^0\pi^+\pi^-$ └→ $\pi^+ + \pi^- + \pi^0$	0.2	$\eta^0\pi^+\pi^-$ └→ neutrals	0.6	$\pi^0\gamma$ $\eta^0\gamma$	~0.2	direct	$\sim\frac{1}{4}$
Observed rate		0.1 ± 0.04		0.4 ± 0.1		0.4 ± 0.2		$\sim\frac{1}{5}$

representing all available $\eta^0\pi^+\pi^-$ decays. These data consist of 102 events from channels (2) and (3) which satisfy restrictive selection criteria defined in detail in references 1 and 2. We estimate that the background contribution consists of somewhere between 17 and 27 events. The data (not shown) can be plotted in terms of coordinates which are generalizations of those used in τ-decay analysis,[12] i.e.,

$$x = \left(\frac{T_+ - T_-}{Q}\right)\left(\frac{M+2m}{M}\right)^{1/2}, \quad y = \left[\left(\frac{M+2m}{m}\right)\frac{T_3}{Q} - 1\right],$$

where m, m, M, T_+, T_-, and T_3 are the masses and kinetic energies of the π^+, π^-, and η, respectively. The I, J^P dependence of the Dalitz plot density (i.e., the square of the X^0 decay matrix element) is analyzed in standard fashion. We describe the $\eta^0\pi^+\pi^-$ final state in terms of the di-pion ($\pi^+\pi^-$) with relative momentum $\vec{q}$ and relative angular momentum $\vec{L}$, together with the η^0, characterized by its momentum $\vec{p}$ and angular momentum $\vec{l}$ with respect to the over-all center of mass. The simplest of all the permissible configurations of l and L and their corresponding nonrelativistic matrix elements $\mathfrak{M}(\vec{q}, \vec{p}, \cos\theta = \hat{p}\cdot\hat{q})$ are listed in Table II, for all possible spin-parity assignments with $J < 3$. The observed variations in y and θ are compared with theoretical distributions in Figs. 3(a) and 3(b).

In spite of the uncertainties contributed by background and final-state interaction effects, the density distribution for all the assignments (I, J^P) except $(0, 0^-)$, $(1, 1^+)$, and $(0, 2^-)$ disagree so markedly with the data that they may be rejected with a high degree of confidence. On the basis of statistical errors only, analysis yields χ^2 probabilities considerably less than 0.1% for all the assignments except the three listed above. The evidence against $(0, 2^-)$, although weaker, is still substantial—here the χ^2 probability is ≈1%. In contrast to these results, very good fits (≈50% χ^2 probability) are obtained for both[13] $(0, 0^-)$ and $(1, 1^+)$. Unfortunately, either of these assignments is consistent with the observed decay-rate pattern. The decay-rate predictions for

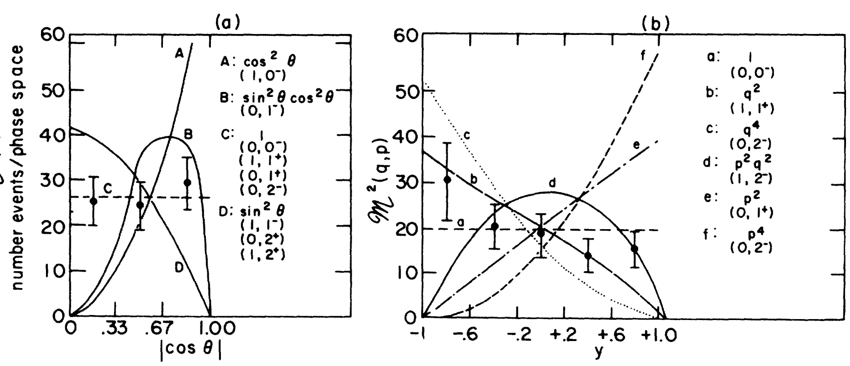

FIG. 3. (a) and (b) Angular and momentum dependence of the square of the (simplest) X^0 decay matrix elements compared with theoretical predictions (see Table I). Background has been subtracted from experimental points.

Table II. X^0 decay matrix elements.

J^P	I	Simplest L,l	$\mathfrak{M}(\vec{q},\vec{p})$	$\mathfrak{M}^2(q,p)$ momentum dependence	$\mathfrak{M}^2(\theta)$ angular dependence
0^+	0	...	Forbidden	...	...
	1	...	Forbidden	...	...
0^-	0	0, 0	1	1	1
	1	1, 1	$\vec{q}\cdot\vec{p}$	q^2p^2	$\cos^2\theta$
1^+	0	0, 1	$\vec{p}$	p^2	1
	1	1, 0	$\vec{q}$	q^2	1
1^-	0	2, 2	$(\vec{q}\cdot\vec{p})(\vec{q}\times\vec{p})$	q^4p^4	$\sin^2\theta\cos^2\theta$
	1	1, 1	$\vec{q}\times\vec{p}$	q^2p^2	$\sin^2\theta$
2^+	0	2, 1	$(\vec{q}\times\vec{p})_\alpha q_\beta + q_\alpha(\vec{q}\times\vec{p})_\beta$	$(q^2p)^2$	$\sin^2\theta$
	1	1, 2	$(\vec{q}\times\vec{p})_\alpha p_\beta + p_\alpha(\vec{q}\times\vec{p})_\beta$	$(qp^2)^2$	$\sin^2\theta$
2^-	0	2, 0	q^2	q^4	1
	0	0, 2	p^2	q^4	1
	1	1, 1	$p_\alpha q_\beta + q_\alpha p_\beta$	p^2q^2	1

$(0,0^-)$ and $(1,1^+)$ are compared with observation in Table I. Finally, we have found no evidence for a charged counterpart of the X^0 in the $\Sigma^\pm+\pi^\mp$ + neutrals system. (This constitutes very weak evidence against $I=1$.)

It is interesting to speculate as to the role of the X^0 within the framework of SU(3).[14] If the assignment $(1,1^{++})$ should be verified, the X^0 presumably heralds the existence of a new unitary multiplet. On the other hand, if $(0,0^{-+})$ is proved correct, the X^0 might be accomodated as a unitary singlet accompanying the η^0, i.e., the $I=0$ member of the pseudoscalar octet. In analogy with the ω-φ situation in the vector-meson octet, the X^0 and η^0 presumably would be mixed.[15] In this case, however, since the observed η^0 mass is within 3 % of the octet mass-formula prediction,[16] the mixing must be negligible. It is also of interest to note that recent generalizations[17] of SU(3) have predicted the existence of a ninth 0^- meson.

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[1]M. Goldberg et al., Phys. Rev. Letters 12, 546 (1964).

[2]G. Kalbfleisch et al., Phys. Rev. Letters 12, 527 (1964).

[3]This sample consists of 10 events from reference 1 and 35 events from reference 2 (produced at all energies 2.45-2.7 BeV/c).

[4]Although correlations certainly do exist here, their effect is small because for this sample the η^0-mass acceptance region is very narrow compared with the range over which $M(3\pi)$ phase space is appreciable.

[5]For $I=0$, the ratio $(X\to\eta^0+\pi^++\pi^-)/(X\to\eta^0+\pi^0+\pi^0)$ $=2/1$. This, together with the η^0-decay branching ratios – 70 % for $\eta^0\to$ neutrals and 24 % for $\eta^0\to\pi^++\pi^-+\pi^0$ [see G. Puppi, Ann. Rev. Nucl. Sci. 13, 287 (1963)]–, gives $(\beta)/(\alpha)=(0.24/2)\times0.7\approx\frac{1}{8}$.

[6]If one considers a model for (β) of the type $X^0\to\eta^0+\sigma^0$, $\eta^0\to\sigma^0+\pi^0$, then the neutral mass spectrum $M^2(\sigma^0\pi^0)$ is essentially flat over the range 500-600 MeV. Including resolution, the η^0 mass from (α) extends over the same region. Since the latter is dominant for either $I=0$ or $I=1$, there is no possibility of distinguishing a contribution from (β), with present statistics.

[7]N. P. Samios, A. H. Bachman, R. M. Lea, T. E. Kalogeropoulos, and W. D. Shephard, Phys. Rev. Letters 9, 139 (1962).

[8]L. Brown and P. Singer, Phys. Rev. Letters 8, 460 (1962); F. S. Crawford, Jr., R. Grossman, L. Lloyd, L. Price, and E. Fowler, Phys. Rev. Letters 11, 564 (1963); L. Brown and P. Singer, Phys. Rev. 133, B812 (1964); R. Del Fabbro et al., Phys. Rev. Letters 12, 674 (1964).

[9]The relatively small observed width of the X^0 ($\Gamma<12$ MeV) is entirely consistent with this hypothesis. Neglecting barriers and taking an interaction radius of M_η^{-1}, we find $\Gamma(X\to\eta+\pi+\pi)\approx10$ keV. Of course, the rate is sensitive to the choice of radius – it increases to 10 MeV, if one takes M_π^{-1}.

[10]This ignores the possibility of a new selection rule which is specially designed to forbid 3π decay. See, for example, J. Bronzan and F. Low, Phys. Rev.

Letters 12, 522 (1964).

[11]This estimate is based on the formulas given by R. H. Milburn, Rev. Mod. Phys. 27, 1 (1955).

[12]R. Dalitz, Phil. Mag. 44, 1068 (1953).

[13]We have also fit the y density with the final-state interaction formula of L. Brown and P. Singer assuming a σ enhancement in the mass range 350-400 MeV and widths in the range 30-100 MeV. A reasonable fit may be obtained only for high mass (~400 MeV) and large width (~90 MeV), in which case the spectrum shape is virtually identical to the 1^+ shape, i.e., a linear q dependence. Thus, the existence of final-state interactions may make it very difficult, if not impossible, to distinguish 1^+ from 0^-, using the Dalitz plot technique.

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[15]J. J. Sakurai, Phys. Rev. Letters 9, 472 (1962); S. Okubo, Proceedings of the Athens Topical Conference on Recently Discovered Resonant Particles, 26-27 April 1963 (Ohio University, Athens, Ohio, 1963), p. 193.

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[17]J. Schwinger, Phys. Rev. Letters 12, 237 (1964); A. Pais, Phys. Rev. Letters 12, 634 (1964).

MAGNITUDE OF THE K_1^0-K_2^0 MASS DIFFERENCE*

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Since Gell-Mann and Pais first pointed out the necessity of a minute mass difference between the K_1^0 and K_2^0 mesons in 1955,[1] there have been six measurements of this quantity reported in the literature.[2-7] These measurements have yielded values ranging from 0.50 ± 0.15 to 1.9 ± 0.3 (in units of $\hbar/\tau_1$ where τ_1 is the mean lifetime of the K_1^0 meson). Although no two experiments were truly identical, they can all be put into two general classes; viz., those which study the development of the $\bar{K}^0$ component in an initially pure K^0 beam[2-5] and those which study coherent regeneration of K_1^0 mesons by a K_2^0 beam.[6,7] With the exception of reference 5, there is a marked tendency for experiments of the first type to give significantly higher values than those of the second type (see Table I). Because most of the experiments are complicated and require elaborate analyses, it is not yet clear whether this discrepancy is due to some new, but unrecognized, phenomenon or is simply a result of the experimental difficulties. In an effort to clarify the experimental side of this problem, we report here a new measurement of the mass difference obtained from a spark chamber study of coherent regeneration as a function of regenerator thickness.[8] This method is relatively simple, involves no subtle corrections, and can be shown to be insensitive to small violations of CP invariance in neutral K decays.

The principle of our method is as follows. When a K_2^0 beam passes through an iron slab of thickness x, the K_1^0 intensity builds up behind the slab due to the difference in strong interactions between the K^0 and $\bar{K}^0$ components with the iron nuclei. In the forward direction, the K_1^0 amplitudes regenerated from different parts of the slab add up coherently and the intensity depends on the mass difference δ as given first by Good,[9]

$$I(x,\delta)=\frac{|\lambda N f_{12}(0,p)\Lambda|^2}{\delta^2+\frac{1}{4}}e^{-x/\mu} \times[1-2e^{-x/2\Lambda}\cos(x\delta/\Lambda)+e^{-x/\Lambda}], \qquad (1)$$

where $\lambda(=h/p)$ is the wavelength of the incoming K_2^0 of momentum p, N the number of nuclei per cm^3, $f_{12}(0)$ the amplitude for forward regeneration by a single nucleus, $\Lambda(=c\tau_1 p/mc)$ the mean decay length of the K_1^0, and μ the nuclear mean free path in iron. We have determined the value of δ by measuring the relative magnitude of $I(x,\delta)$ as a function of x. For this purpose, it was necessary to know the momentum of each event, to measure the nuclear mean free path μ, and to separate the coherent regeneration from the diffraction regeneration. It should be emphasized that this method does not require a knowledge of the regeneration amplitude $f_{12}(0,p)$ and is free from any multiple-scattering correction to the diffraction regeneration.[4]