DECAY MODES OF THE 960-MeV $\eta\pi\pi$ RESONANCE*

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The discovery of a new meson of mass about 960 MeV has been recently announced by two independent groups.[1,2] The method of production ($K^- + p \to \Lambda + X^0$) shows that it must have isospin $T = 0$ or 1. The only well-established decay mode is $X^0 \to \pi^+ + \pi^- + \eta$, which includes about half of the identified X^0 events, almost all of the remaining events consisting of decays of the type $X^0 \to$ all neutrals. Within the available statistics, the number of neutral decays is consistent with $X^0 \to \pi^0 + \pi^0 + \eta$ being the companion mode to $\pi^+\pi^-\eta$. The absence of measurable decay into two, three, or four pions, together with the observation that five-pion decays almost always include three pions having total charge zero and effective mass corresponding to the η meson, leads to the conjecture that spin-parity-G-parity assignment is either 0^{-+} or 1^{++}, with 0^{-+} being favored by the low rate of $X^0 \to 4\pi$.[3,4]

Assuming that X^0 has $TJ^{PG} = 00^{-+}$ and that it decays mainly via the strong interactions, we show that the dominance of the $\pi\pi\eta$ mode implies that the principal mechanism is

$$X^0 \to \eta + \underset{\hookrightarrow \pi\pi}{\sigma} \tag{1}$$

where σ is an isosinglet neutral scalar meson.[5] We estimate the decay width for this process using an extension of the Coleman-Glashow notion of a unitary-symmetric scalar-meson coupling of universal strength.[6] We also obtain the branching ratios into subsidiary decay modes, including the electromagnetic modes. An interesting point is implied by this work: If the "A invariance" of Bronzan and Low[7] is relevant to decay processes, then X^0 must have $A = -1$.

Disregarding for the moment the σ meson, the allowed strong decays are into the modes $\pi\pi\eta$, 4π, and 6π; we shall assume the last to be negligible. A conservative estimate of the four-pion partial decay width is $\Gamma_{X^0}(4\pi) < 1$ keV. This is based on the lowest possible angular-momentum configuration, that corresponding to two neutral di-pions having the quantum numbers of the ρ^0 meson. This rate is negligible compared with other partial rates discussed below. A straightforward calculation of $X^0 \to \pi^+ + \pi^- + \eta$, assuming a structureless vertex with effective coupling $G'X^0\pi^+\pi^-\eta$, gives the result

$$\Gamma_{X^0}(\pi^+\pi^-\eta) = 2G'^2 \text{ keV}, \tag{2}$$

where G' is expected to be of order unity.

The calculation of the rate for process (1) is exactly analogous to the calculation of $\eta \to \sigma + \pi^0$ given in reference 5, except for omission of the factor $\alpha = 1/137$ in the present case. The results are

$$\Gamma_{X^0}(\pi^+\pi^-\eta) = G^2 g^4 [(4\pi)^3 4 m_{X^0}^3]^{-1} I, \tag{3}$$

where

$$I = \int_{m_\eta}^{\omega_{\max}} \frac{\varphi(\omega)d\omega}{(A + m_\eta - \omega)^2 + B^2}, \tag{4}$$

$$A = [(m_{X^0} - m_\eta)^2 - m_\sigma^2]/2m_{X^0}, \tag{5}$$

$$B = m_\sigma \Gamma_\sigma / 2m_{X^0}, \tag{6}$$

$$\varphi(\omega) = (\omega^2 - m_\eta^2)^{1/2} (m_{X^0}^2 + m_\eta^2 - 4\mu^2 - 2m_{X^0}\omega)^{1/2} \times (m_{X^0}^2 + m_\eta^2 - 2m_{X^0}\omega)^{-1/2}, \tag{7}$$

$$\omega_{\max} = (m_{X^0}^2 + m_\eta^2 - 4\mu^2)/2m_{X^0}, \tag{8}$$

and μ is the mass of the charged pion. The quantity g is the $\sigma\pi^+\pi^-$ coupling and is related to the mass m_σ and the width Γ_σ of the σ meson by

$$g^2 = \Gamma_\sigma (32\pi m_\sigma^2)/3(m_\sigma^2 - 4\mu^2)^{1/2}. \tag{9}$$

With $m_\sigma = 400$ MeV and $\Gamma_\sigma = 100$ MeV, one obtains $(g^2/4\pi m_\sigma^2) = 0.93$. The rate for $X^0 \to \pi^0 + \pi^0 + \eta$ is given by one half of the expression (3) with μ_0, the neutral pion mass, substituted everywhere for μ.

As a first approach, we may consider equating the coupling constant at the $X^0\eta\sigma$ vertex (which we have denoted by gG) with the corresponding constant appearing at the $\sigma\pi^+\pi^-$ vertex, since we have assumed the vertices to have identical structure except for isospin considerations; this is equivalent to the choice $G = \frac{1}{2}$. However, from the viewpoint of SU(3) symmetry this procedure may be questioned, since it is believed that X^0 is a unitary singlet. To make another estimate, let us assume that the σ meson has SU(3) octet transformation properties[8] and is identical with the isosinglet scalar tadpole meson of Coleman and Glashow.[6] These authors have argued, on the basis of observed equal spacing in mass squared between the corresponding members of the meson octets, that the scalar meson octet is coupled with a universal strength to the octets of pseudoscalar mesons and vector mesons and to itself. In terms of the coupling constant g which we assigned to the $\sigma\pi^+\pi^-$ vertex, this Coleman-Glashov coupling constant,[9] here denoted by g', is $g'=(\sqrt{3}/4)g$ and enters as the coefficient of that term in the interaction Lagrangean which describes the SU(3) invariant interaction of three meson octets: for example, $g'\,\mathrm{Tr}\Phi\Phi\Phi'$, where Φ' is the scalar and Φ is the pseudoscalar octet.[9] The SU(3)-invariant coupling of a unitary singlet with two octets is $g'X^0\,\mathrm{Tr}\Phi\Phi'$, where we have here extended the notion of scalar meson coupling universality by using the same g'.

In Table I we give the value of $\Gamma_{X^0}(\pi^+\pi^-\eta)/G^2$ calculated from Eq. (3), with $m_{X^0}=960$ MeV, for several values of m_σ and Γ_σ. The branching ratio $\Gamma_{X^0}(\pi^0\pi^0\eta)/\Gamma_{X^0}(\pi^+\pi^-\eta)=0.535$; thus the total width is effectively given by $1.535G^2\Gamma_{X^0}(\pi^+\pi^-\eta)$. For $m_\sigma=400$ MeV, $\Gamma_\sigma=75$ MeV, and with $gG=(\sqrt{3}/2)g$ the total width is 2.3 MeV.[10]

Since confidence in our methods for dealing with the electromagnetic modes of X^0 must rest largely on reasonable agreement with experiment obtained for the analogous modes of the η meson,[5,11] we wish to refine the dimensional estimates contained in the second paper of reference 5.[12] In that paper we calculated $\Gamma_\eta(2\gamma)$ and $\Gamma_\eta(\pi\pi\gamma)$ by assuming the two-step processes $\eta\to\gamma+\rho\to\gamma+\gamma$ and $\eta\to\gamma+\rho\to\gamma+\pi^++\pi^-$ in which the first common vertex ("black box") was assigned an effective coupling constant K. On dimensional grounds we estimated $K^2\approx\alpha/m_\rho^{\ 2}$. As a test the model was applied (using $\pi^0\to\rho+\omega\to2\gamma$) to the calculation of the π^0 lifetime, and it gave good agreement with the (old) value $\tau_{\pi^0}=2.2\times10^{-16}$ sec using the above value of K^2. A new lifetime

Table I. Values (in MeV) of $\Gamma_{X^0}(\pi^+\pi^-\eta)/G^2$.

m_σ (MeV) \ Γ_σ (MeV)	100	75	50
425	1.55	1.13	0.67
400	2.45	2.01	1.48
375	3.54	3.06	2.42

$\tau_{\pi^0}=1.05\times10^{-16}$ sec has been subsequently obtained.[13] In the "black box" picture where we used $K^2=\alpha/m_\rho^{\ 2}$ to obtain the old π^0 lifetime we must use $2\alpha/m_\rho^{\ 2}$ to obtain the new one. Furthermore, if in our comparison of the π^0 and η coupling strengths we use SU(3) coefficients,[14] we find the ratio of effective strengths $(\pi^0\to2\gamma):(\eta^0\to2\gamma):(\eta^0\to\pi\pi\gamma)$ to be 3:1:9/4. Where previously we used $K^2=\alpha/m_\rho^{\ 2}$ in each of these processes, we now use $2\alpha/m_\rho^{\ 2}$, $2\alpha/3m_\rho^{\ 2}$, and $3\alpha/2m_\rho^{\ 2}$, respectively (based on the new π^0 lifetime). Whereas we previously obtained $\Gamma_\eta(2\gamma)\approx160$ eV, $\Gamma_\eta(\pi^+\pi^-\gamma)\approx20$ eV, we now obtain $\Gamma_\eta(2\gamma)\approx107$ eV and $\Gamma_\eta(\pi^++\pi^-+\gamma)\approx30$ eV; the ratio $\Gamma_\eta(2\gamma)/\Gamma_\eta(\pi\pi\gamma)\approx4$, which can be compared with the experimental value[15,16] of ≈5. The $\eta\to3\pi$ rate obtained in the first paper of reference 5 (of the order of 100 eV) is also consistent with the experimental picture.

The decay modes of X^0 involving photons, real or virtual, include those previously considered in the decay of the η meson, namely 3π, $\pi\pi\gamma$, 2γ, and $\pi\gamma\gamma$. In addition, in the case of X^0, a possibly significant decay mode is $X^0\to\omega+\gamma$, which would appear as $\pi^+\pi^-\pi^0\gamma$ or, with about a 10% branching ratio, as $\pi^0\gamma\gamma$. The rates for these processes are calculated by the methods of reference 5, which have given reasonable results for the analagous η-meson decay rates. In the present case we merely quote our results (Table II) indicating the relevant intermediate states employed. The A-parity number of the final state, following the assignments of Bronzan and Low,[7] is included in Table II, and will be discussed below, although the rates have been calculated completely disregarding the A parity.

We believe the branching ratios implied by Table II are roughly correct, and that the absolute values are of the right order of magnitude. As the X^0 presumably constitutes a new unitary multiplet, we cannot really know its coupling strength to any of the other multiplets. But for definiteness we assume a coupling $g'X^0\,\mathrm{Tr}\Phi\Phi$, and take for g' the same value as occurs in the coupling $g'\,\mathrm{Tr}\Phi\Phi\Phi$ which applies to the η electromagnetic decays discussed above.[17]

A comparison of the rates for the various decays, strong and electromagnetic, demonstrates that it is consistent with the experimental observations to assume that X^0 decays primarily through the channel $X^0\to\sigma+\eta\to2\pi+\eta$. On the other hand, the relatively low rate calculated for $X^0\to\pi+\pi+\eta$ without the σ mechanism is comparable to the rate obtained for the charged elec-

Table II. Partial rates for X^0 electromagnetic decays. For the 3π modes, σ is assumed to have m_σ=400 MeV, Γ_σ=75 MeV. The rates given are approximate; for details see text.

Decay mode	Electromagnetic order	"Black box" coupling	Intermediate state	Partial rate (keV)	A parity
$\pi^+\pi^-\pi^0$	α^2	...	$\sigma+\pi^0$	0.7	-1
$\pi^+\pi^-\gamma$ [a]	α	$9\alpha/2m_\rho^2$	$2\rho^0$	108	+1
2γ	α^2	$8\alpha/m_\rho^2$	$2\rho^0$ or $2\omega^0$	7	+1
$\omega\gamma$	α	$3\alpha/2m_\rho^2$	$2\omega^0$	32	-1

[a]Including $\rho^0\gamma$.

tromagnetic modes, and is inconsistent with the observation that the X^0 events not identified as $\pi^+\pi^-\eta$ are almost entirely neutral. In fact, using the σ mechanism we estimate that the total of all non-$\pi\pi\eta$ decays are about 10%. A measurement of the branching into one or more of these minor modes would not only test the present model, but would permit an estimate of the strong interaction width. This in turn would test the theoretical assumptions used in obtaining this width, in particular whether the σ meson has octet properties or behaves as a unitary singlet, for in the latter case we would expect a smaller width, as $X^0\to\sigma+\eta$ would be an SU(3)-forbidden transition. An additional test of the σ mechanism is furnished by the $\pi\pi$ effective mass spectrum in the decay $X^0\to\eta+\pi^++\pi^-$. Our calculated spectrum is shown in Fig. 1.

Finally, if A invariance is relevant to these processes,[18] then $A_{X^0}=-1$, for with this assignment $X^0\to\pi+\pi+\eta$ is an allowed decay (with or without the σ mechanism) as is $X^0\to 3\pi$, while the Gell-Mann–Sharp–Wagner mechanism is forbidden. The effect would be to reduce still further the rates for the $\pi\pi\gamma$, 2γ, and $\omega\gamma$ modes, which would not contradict the observations. On the other hand, if $A_{X^0}=+1$ then $\pi\pi\eta$ is forbidden and the above three modes would become more prominent than is permitted by the present data.

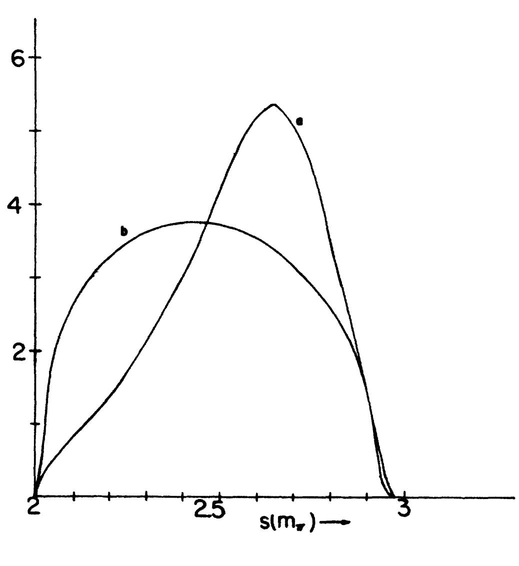

FIG. 1. Spectrum of the effective mass s of the two pions in the decay $X^0\to\eta+\pi^++\pi^-$ for the cases (a) $\pi\pi$ final state interaction with m_σ=400 MeV, Γ_σ =75 MeV; (b) phase space only.

[1]G. R. Kalbfleisch, L. W. Alvarez, A. Barbaro-Galtieri, O. I. Dahl, P. Eberhard, W. E. Humphrey, J. S. Lindsay, D. W. Merrill, J. J. Murray, A. Rittenberg, R. R. Ross, J. B. Shafer, F. T. Shively, D. M. Siegel, G. A. Smith, and R. D. Tripp, Phys. Rev. Letters 12, 527 (1964). These authors give the mass as 959 ± 2 MeV and the width as $\Gamma<12$ MeV.

[2]M. Goldberg, M. Gundzik, S. Lichtman, J. Leitner, M. Primer, P. L. Connolly, E. L. Hart, K. W. Lai, G. London, N. P. Samios, and S. S. Yamamoto, Phys. Rev. Letters 12, 546 (1964); and M. Goldberg et al., Bull. Am. Phys. Soc. 9, 23 (1964). These authors give the mass as 960 ± 5 MeV and the width as $\Gamma<20$ MeV. They have suggested the tentative name X^0, which we shall adopt in this work.

[3]Additional arguments and data bearing on the spin-parity assignment are made in reference 1 and in private communication from J. Leither and N. P. Samios. For the 1^{++} assignment we estimate the 4π rate to be a few keV and we obtain a rate of about 10 keV for $X^0\to\pi\pi\eta$, assuming for this process the mechanism of Eq. (1), below.

[4]K. Itabashi, to be published.

[5]L. M. Brown and P. Singer, Phys. Rev. 133, B812 (1964), and Phys. Rev. Letters 8, 460 (1962). The mass and width of the σ meson, on the basis of η- and K-meson decays into three pions, are $m_\sigma\approx 390$ MeV and $\Gamma_\sigma\approx 75$ MeV.

[6]S. Coleman and S. L. Glashow, Phys. Rev. 134, B671 (1964).

[7]J. B. Bronzan and F. E. Low, Phys. Rev. Letters 12, 522 (1964).

[8]In this connection, we disregard the question of whether the σ necessarily has "octet partners."

[9]Compare Eq. (2) of reference 6. The 3×3 matrices Φ as given by S. Coleman and L. Glashow, Phys. Rev. Letters 6, 423 (1961), have been multiplied by $\sqrt{2}$ in

reference 6 and we have done the same.

[10]We emphasize that this estimate is based on the assumption that X^0 is a unitary singlet and that σ and η are unitary octet members. Other assumptions regarding the unitary character of X^0 and σ would lead to other values for the width. For X^0 and σ both octet members we would take $G=\frac{1}{2}$, giving $\Gamma_{X^0}=770$ keV. If X^0 and σ were both unitary singlets, then $X^0 \rightarrow \sigma+\eta$ would be forbidden by SU(3) invariance, in contrast to $\sigma \rightarrow \pi+\pi$, hence our estimate in that case could be smaller than 0.5 MeV. Finally, under the radical assumption that X^0 is an octet and σ a singlet, we again obtain $G=\frac{1}{2}$.

[11]M. Gell-Mann, D. Sharp, and W. G. Wagner, Phys. Rev. Letters 8, 261 (1962).

[12]We wish to thank Professor Paul Singer for discussions of these estimates.

[13]G. von Dardel, D. Dekkers, R. Mermod, J. D. van Putten, M. Vivargent, G. Weber, and K. Winter, Phys. Letters 4, 51 (1963).

[14]At the strong vertices $\eta \rightarrow 2\rho^0$, etc., within the "black box." We neglect the contribution of φ.

[15]E. C. Fowler, F. S. Crawford, Jr., L. J. Lloyd, R. A. Grossman, and L. Price, Phys. Rev. Letters 10, 110 (1963).

[16]F. S. Crawford, Jr., L. J. Lloyd, and E. C. Fowler, Phys. Rev. Letters 10, 546 (1963).

[17]K. Itabashi (reference 4) has made the interesting remark that if X^0 is a unitary singlet, it is also a U-spin singlet implying, for example, the relation $\Gamma_{X^0}(\rho^0\gamma)=3\Gamma_{X^0}(\omega_0\gamma)$, where ω_0 is the $T=0$ member of the vector meson octet. If we write ω_0 as an equal mixture of the physical ω and $\varphi(1020)$ and neglect the latter, as we have done throughout this work, this prediction is roughly consistent with our more dynamical calculation, also based on the assumption that X^0 is a unitary singlet.

[18]In reference 7 the authors have remarked that perhaps the η-meson decays are to be explained by a combination of A invariance and the σ mechanism, the former suppressing the decays involving photons (except $\pi\gamma\gamma$) and the latter enhancing the 3π mode and accounting for its Dalitz plot. No suppression of the $\pi\pi\gamma$ and 2γ appears necessary in our picture of the η decays.