[10] The charge conjugation operator has eigenvalues -1 for a γ, +1 for a π^0, and $(-1)^l$ for a $\pi^+\pi^-$ pair.

[11] The pure 3π-decay rate of the 0^{--} η is proportional to $(k_{\text{av}})^{12}Q^2$ in the isospin-conserving decay, a factor of $(k_{\text{av}})^8$ smaller than the usual phase-space calculation. A small violation of isospin conservation changes the Dalitz plot drastically but increases the decay rate only by a factor of ~ 2 as shown in Table I. Thus the $3\pi+\gamma$ mode can compete favorably with the 3π decay, which is anomalously slow.

[12] Footnote 7 of reference 2.

[13] G. Chew and F. Low, Phys. Rev. 113, 1640 (1959).

[14] This assumes the K^* has $I=\frac{1}{2}$ in agreement with experiment.

[15] A. H. Rosenfeld (private communication); A. H. Rosenfeld, D. D. Carmony, and R. T. Van de Walle, Phys. Rev. Letters 8, 293 (1962).

[16] A calculation of the Dalitz plot for a 0^{--} $\omega \to \pi^+ + \pi^- + \pi^0$, done by inserting the ω mass for the η into (3), showed no large cancellations of the matrix elements and no sensitivity to small violations of I. (This is as expected because the ω decay has a large Q value.) This not only lends support to the 1^{--} assignment for the ω but gives us more faith in our calculation for the η.

[17] M. Gell-Mann, Phys. Rev. 125, 1067 (1962); J. Sakurai, Ann. Phys. (New York) 11, 1 (1960).

PIONIC NUCLEI

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The search for peaks in the spectra of production reactions has recently disclosed the existence of a neutral particle, η^0,[1-3] and a singly charged particle, ζ^+,[4,5] both with mass about 550 Mev. A similar particle, ζ^-, has also been reported.[6] The η^0 is observed to decay into $\pi^+ + \pi^- + \pi^0$ and also in purely neutral modes. The $\zeta^\pm$ decays into $\pi^\pm + \pi^0$. The most attractive explanation of the near equality of the η^0 and ζ masses would be that they are different members of a charged multiplet. However, there seems to be some evidence[3,7] that the η^0 has isotopic spin 0, while the ζ, produced in the reaction $p+p \to d+\zeta^+$, must have isotopic spin 1.[5] It is therefore a puzzle why their masses should be nearly equal and should be so close to four pion masses.

The main purpose of this note is to point out that this is no longer puzzling if we interpret the η^0 and ζ as loosely bound nuclei made up of four pions, with quantum numbers which forbid two-pion and three-pion decays in the absence of electromagnetic interactions.[8] We imply here no more, and no less, than the usual imprecise distinction between an elementary particle and a compound system which one customarily makes in describing, say, the helium particle as a compound system made up of "elementary nucleons."

Bastien *et al.*[2] have already presented arguments for assigning to the η^0 the quantum numbers 0^{-+} where (here and below) the number refers to the spin, the first superscript to ordinary parity, and the second to G parity. This is consistent with the suggestion above since, on this picture, η^0 decays into three pions only through (presumably electromagnetic) G-parity nonconserving effects, while it is strongly coupled to the 4π system, which has $G=+1$.

Restricting ourselves to spins 0 or 1, we would like to suggest a set of quantum numbers for the ζ meson which would allow it to be interpreted similarly. For such a scheme to work we must suppose that the observed two-pion decay mode of the $\zeta^\pm$ occurs only through the intervention of electromagnetic effects; i.e., that it is forbidden by purely strong interactions. This would imply that the width of the charged ζ "resonance" in the 2π system is small, where we can take the 2π decay of the ρ meson as a standard of comparison. There is good evidence[5] that this width is indeed small.

Our scheme should also forbid the decay $\omega^0 \to \zeta + \pi$ by strong interactions; the correlations which such a decay would produce in the resulting three-pion spectrum from ω^0 decay do not appear to have shown up in the Dalitz plot analyses.[9] We shall use the assignment 1^{--}, $I=0$ for the ω^0. Note that the decay $\omega^0 \to \eta^0 + \pi^0$ is forbidden by charge conjugation invariance.

These requirements lead us to the quantum numbers 0^{++}, $I=1$, for the ζ meson. That the isotopic spin is in fact unity we of course already know experimentally, as mentioned above.

It should be emphasized that we cannot give any a priori argument from the dynamics of the 4π system that it must bind, and still less that it should produce two bound states. However, experience with ordinary nuclei indicates that binding, once it is at all possible, can often occur in several configurations. Given the two coincidences—that the η^0 and ζ have nearly the same mass, and that this mass is close to the four-pion threshold—the interpretation of these as pionic nuclei appears reasonable.

Whatever the interpretation, our assignment of the quantum numbers 0^{++} $(I=1)$ for the ζ particle implies the following:

1. $\zeta \rightarrow 3\pi$ decay is absolutely forbidden by spin-parity conservation.

2. $\omega^0 \rightarrow \zeta + \pi$ decay is absolutely forbidden by spin-parity conservation with the ω^0 quantum numbers taken to be 1^{--} $(I=0)$. The reactions $\rho \rightarrow \eta^0 + \pi$ and $\rho \rightarrow \zeta + \pi$ are forbidden as strong processes by G-parity conservation; and, as already noted, $\omega^0 \rightarrow \eta^0 + \pi^0$ decay is forbidden by charge conjugation invariance.

3. With the exception of the decay $\zeta \rightarrow 4\pi$, which at most is just allowed energetically, all decay modes of the ζ meson must involve violations of isotopic spin conservation. Hence the ζ-meson widths are expected to be small. The same remark holds for the η^0 meson.

4. The decay $\zeta \rightarrow \pi + \gamma$ is, of course, forbidden as a $0 \rightarrow 0$ electromagnetic transition. The dominant decay modes of the charged ζ mesons will be $\zeta^{\pm} \rightarrow \pi^{\pm} + \pi^0$ and perhaps $\zeta^{\pm} \rightarrow \pi^{\pm} + \pi^0 + \gamma$.

5. For the neutral ζ meson, the decay $\zeta^0 \rightarrow 2\pi$ is absolutely forbidden by charge conjugation invariance. (By spin conservation the final state would have to have isotopic spin $I=0$ or 2; but these states are even under charge conjugation, whereas ζ^0 is odd under charge conjugation.) For the same reason $\zeta^0 \rightarrow 2\gamma$ decay is forbidden. The decay $\zeta^0 \rightarrow 2\pi + \gamma$ is allowed and presumably constitutes the dominant mode of ζ^0 disintegration. The final pions here must be in states with isotopic spin $I=0$ or 2; hence the transition is at least electric quadrupole. Barring accidental cancellations, both of the modes $\zeta^0 \rightarrow 2\pi^0 + \gamma$ and $\zeta^0 \rightarrow \pi^+ + \pi^- + \gamma$ are to be expected. For the η^0 meson the dominant modes of decay are expected to be $\eta^0 \rightarrow 2\gamma$, $\eta^0 \rightarrow \pi^+ + \pi^- + \gamma$ ($\eta^0 \rightarrow 2\pi^0 + \gamma$ is forbidden), and of course $\eta^0 \rightarrow 3\pi$. In reactions which can produce either ζ^0 or η^0, there will be some difficulty in distinguishing between them in their purely neutral decay modes and in the mode $\pi^+ + \pi^- + \gamma$. For example, in K^--p collisions the reactions,

$$K^- + p \rightarrow \Lambda + \eta^0,$$

$$K^- + p \rightarrow \Lambda + \zeta^0,$$

may both occur.

6. We may remark that if the η^0 and ζ particles are really loosely bound pionic nuclei, one might expect, by analogy with ordinary nuclear fragments, that the cross sections for their production will in general fall off rapidly with increasing energy above threshold. There is some evidence for this in the reaction $K^- + p \rightarrow \Lambda^0 + \eta^0(\zeta^0 ?)$.[2] There is also evidence from experiments on pion production in $\pi^+ p$ collisions[4] and $\pi^- p$ collisions[6] that the ζ-production cross sections decrease with increasing energy and are small by 1.2 Bev.

7. Finally there is the question whether one may expect to see other bound four-pion states. As we have already indicated, we cannot derive the η^0 or ζ from the dynamics of four-pion interactions but we merely observe that they are possible bound states, stable or perhaps just metastable against strong decays. There are many other configurations of the four-pion system which could also be candidates for bound states, stable against strong decays into two pions (three-pion decay being automatically forbidden as a strong process by G-parity conservation): for example, all states with spin J and parity $\pi = -(-1)^J$, irrespective of isotopic spin; and all states with isotopic spin $I=3$ or 4, irrespective of spin or parity. The situation around 550 Mev could turn out to be very complicated indeed.

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[8] The strong interaction decays into four pions may just be energetically allowed; i.e., strictly speaking, our nuclei may be only metastable even with respect to the strong interactions. In actual fact, however, four-pion decay should be negligibly slow.

[9] B. Maglić, L. Alvarez, A. Rosenfeld, and M. Stevenson, Phys. Rev. Letters 7, 178 (1961). Note that unless forbidden, such a strong two-body decay should in fact predominate in the ω^0 decay and thus these correlations should be very strong.

PROPERTIES AND EFFECTS OF ζ DECAYS

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Several recent experiments[1–4] seem to indicate the existence of charged particles, called $\zeta^\pm$, with a mass of about 560 Mev. The limited evidence points to the isotopic spin assignment $T=1$ for ζ, insofar as production is concerned. In the one experiment[4] in which 2π can only be produced in a pure $T=1$ state, the ζ^+ width appears to be small. It is the purpose of this note to emphasize the importance of the relative properties of $\zeta^\pm$ and ζ^0 and to consider the influence of ζ on other pion resonances as well as on weak interactions.

The argument hinges on the 2π-decay properties of ζ and more specifically on the behavior of ζ^0 under charge conjugation. We consider three alternatives denoted by (a), (b1), and (b2) and show that these may be distinguished by measuring the 2π-decay modes of the ζ's.

(a) $\zeta \to 2\pi$ is T-allowed. Therefore ζ has odd angular momentum and even G. In this case,[5]

$$\text{(a)}\ \Gamma(\zeta^+ \to \pi^+\pi^0) = \Gamma(\zeta^0 \to \pi^+\pi^-), \quad \Gamma(\zeta^0 \to 2\pi^0) = 0, \tag{1}$$

so that ζ^+ and ζ^0 have essentially the same width. The relevance of this obvious remark lies in the following. It has been pointed out[6] that the decay of ω^0 into $\zeta + \pi$ [allowed by assumption (a)] would lead to a characteristic band effect in the Dalitz plot for ω^0. It was further observed[7] that in this case $\omega^0 \to \zeta + \pi$ would actually be the most prominent π^0 mode, provided that the dimensionless effective (ω^0, ζ, π) coupling constant is ~1. No band structure in the ω^0-decay plot has been reported. Thus if Eq. (1) were to be true experimentally, we would have learned that the coupling constant just mentioned is small (which cannot be excluded by any principles we know of).

If Eq. (1) is in disagreement with experiment, we learn that $\zeta \to 2\pi$ is not T-allowed, which would be consistent with a narrow width. If this is the case, ζ must have even spin. This opens the possibility of assigning a spin and parity to ζ in such a way as to forbid the decays $\omega \to \zeta + \pi$, $\rho \to \zeta + \pi$. The unique assignment which does this is zero spin, even parity.

While in case (a) it follows automatically that ζ^0 is odd under charge conjugation (C), we have now further to distinguish two cases.

(b1) $\zeta \to 2\pi$ is T-forbidden and ζ^0 is odd under C; hence ζ is even under G. In a recent note,[8] Peierls and Treiman discussed the assignment 0^+ for spin and parity of ζ. They were forced to take ζ^0 odd under C because they consider the ζ to be something like a 4π molecule, a picture which we find hardly compelling. Assumption (b1) gives

$$\text{(b1)}\ \Gamma(\zeta^0 \to \pi^+\pi^-) = \Gamma(\zeta^0 \to 2\pi^0) = 0, \tag{2}$$

and the principal ζ^0 mode is $\zeta^0 \to \pi\pi\gamma$ ($\zeta^0 \to 2\gamma$ is also forbidden). As was pointed out,[8] in this case the lowest multipole order is $E2$. The width of ζ^0 should therefore be much smaller than the one for ζ^+ which does decay into 2π by electromagnetic violation of T. See the remark after Eq. (5) below.

(b2) $\zeta \to 2\pi$ is T-forbidden and ζ^0 is even under C; hence ζ is odd under G. In general, both ζ^+