SPLIT PEAKS AND EXOTIC RESONANCES*

Richard C. Arnold
Argonne National Laboratory, Argonne, Illinois 60439

and

J. L. Uretsky
Argonne National Laboratory, Argonne, Illinois 60439 and Northern Illinois University, DeKalb, Illinois 60115

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The existence of exotic mesons is inferred from the apparent splitting of the A_2 peak.

In a contribution[1] to the recent conference on $\pi\pi$ and $K\pi$ interactions at Argonne, Coyne has reported an experiment demonstrating the isospin- and G-nonconserving decay $\omega \rightarrow 2\pi$ as a negative interference "notch" in a $\pi^+\pi^-$ mass histogram in the ρ^0-meson peak. With the "notch" the ρ appears as a twin peak, thereby suggesting that other twin peaks in nature arise from similar causes. Since a double peaking has been observed in the A_2-meson resonance[2] we conjecture that this also arises from a destructive interference in the decays of two different resonances, coherently produced, into the same final state.

We shall consider in this Letter only the most interesting possibilities, namely, that the interfering resonance has different isospin and/or G parity from the A_2 and mixes by virtue of electromagnetic interactions. Thereby rejected vigorously is the ugly possibility that A_2 represents a dipole that arises without sufficient cause.

Since the A_2 has a width of about 90 MeV and is seen to split into two 30-MeV-wide peaks separated by a 30-MeV-wide valley one can conclude that the interfering resonance has a width less than 30 MeV. From the symmetric appearance of the splitting the mass of that resonance must be very nearly degenerate with that of the A_2. The spin and parity is 2^+. The splitting was observed in the CERN $\pi^-p \rightarrow X^-p$ (missing X^- mass) experiment[2] so the only possible isospins are 1 and 2. Presuming that either the isospin or G parity differs from that of the A_2 (1^-), the allowable I^G quantum numbers are 1^+, 2^-, and 2^+. Since a meson with any of these I^G quantum numbers and $J^P = 2^+$ cannot be formed from a quark and antiquark (or nucleon and antinucleon) pair we shall call it "exotic" and denote it by the symbol $\aleph$ (the Hebrew letter aleph).

Information concerning the G parity of $\aleph$ may be obtained by looking for the interference in the decay of the neutral A_2. For the neutral $\aleph$ charge-conjugation invariance forbids electromagnetic mixing with the A_2 if I^G is 1^+ or 2^- but allows it if the quantum numbers are 2^+. For example, if a double peak were found in the $K_1^0K_1^0$ mass spectrum we would conclude that I^G is 2^+. Present evidence is still inconclusive.[3]

A possibly crucial experiment for our scheme is $pd \rightarrow \text{He}^3 +$ (missing mass). Since $I = 0, 1$ are the only possibilities for missing mass, a split A_2 peak in this experiment would demolish our model.

Some further properties of $\aleph$ may be inferred just from the fact that the interference is observable. It must be produced at least as copiously (presumably through t-channel meson exchanges) as the A_2 in meson-baryon collisions. On the other hand, it must have small decay probability into well-explored low-lying states such as $\pi\pi$, $\pi\rho$, and $\pi\omega$ (in the three cases $I^G = 2^+, 2^-, 1^+$) or (1) it would have already been detected and (2) it would be difficult to account for its narrow width. In order to account for these properties we will postulate a selection rule to inhibit the aforementioned decays and simultaneously invoke t-channel exchanges for production that do not violate this rule.

The specific selection rule indicated is that decay of $\aleph$ into a pair of members of the low-lying $\underline{36}$ representation of U(6) is severely inhibited or forbidden.[4] Such a selection rule should effectively decouple $\aleph$ from the unwanted decay modes yet permit production by exchange of suitable meson trajectories (e.g., A_2 if $I^G = 1^+$ or 2^+, or ρ in the case of 2^-). Then allowed decays are πA_1 if $\aleph$ has I^G quantum numbers 1^+ and 2^+, and π plus a virtual B meson if the quantum numbers are 2^-. In either case the Q values are small and an angular momentum barrier is operative so that the "forbidden" decay modes $\pi\omega$, $\pi\rho$, or $\pi\pi$, respectively, for $I^G = 1^+, 2^-, 2^+$ might make an appreciable contribution to the total width.[5]

We now discuss a theoretical framework in which one can understand the existence of new families of mesons and the $\aleph$-A_2 degeneracy in a larger context.[6] Unless the degeneracy is the result of an accident one might suppose that it arises from a symmetry with an associated multiplet structure. The simplest approach is to use the quark model and require that both mesons contain the same number of quarks. As will be seen, the model is somewhat more satisfying if $\aleph$ has quantum numbers $I^G = 2^+$ (so that it can be made from a $qq\bar{q}\bar{q}$ system with no orbital angular momentum), and this will be assumed in the rest of the discussion.

Suppose that the multiplet containing A_2 and $\aleph$ (which also must contain the usual $J^{PG} = 2^+, 1^{++}, 1^{+-}, 0^{++}$ nonets) is composed of 2 s-wave $q\bar{q}$ pairs. Then it is natural to suppose that the multiplets containing mesons of increasingly higher spin are formed by the s-wave addition of more s-wave $q\bar{q}$ pairs. For each multiplet (characterized by the number of $q\bar{q}$ pairs) there will be, along with the normal nonet structures, a brotherhood of exotic mesons, some with isospin greater than unity and/or "abnormal" G parities. For such a picture of the meson spectrum to be useful it is necessary that two requirements be fulfilled: (1) It must provide a selection rule that decouples the exotic mesons from pairs of $q\bar{q}$ mesons and (2) it must contain the multiplet structure and decay relationships of the pure $q\bar{q}$ orbital excitation model.

In fact, a selection rule of the type we need has already been proposed by Freund, Rosner, and Waltz[7] based upon duality requirements and theories of the Pomeranchukon. Consider a three-particle vertex in which particle a has n_a quarks (plus antiquarks), b has n_b, etc.; this vertex should be forbidden unless the condition $n_2+n_3 \geq n_1+2$ is satisfied for every permutation of (a, b, c). This condition prevents coupling of those mesons with more than one $q\bar{q}$ pair to the usual low-lying meson states. The rule thereby allows introduction of $q\bar{q}$-excited heavy mesons for consistent theories of baryon-antibaryon interactions without destroying consistent models incorporating duality for the meson family. However, if the A_2 is to be a four-quark system the selection rule just stated is too strict as it forbids the dominant $\rho\pi$ decay of A_2 (as well as the undesired decay modes of $\aleph$).

Fortunately, a simple modification results in the selection rule needed. Suppose the A_2 (and its Regge recurrences) are built from a $q\bar{q}$ pair which carries the quantum numbers of the internal symmetries, plus a unitary-singlet spin-triplet $q\bar{q}$ pair which we denote by ω_1 (in the case of recurrences there would be several such ω_1's with spins aligned). We can then relax the original rule by making the following exception: If particle 1 has any ω_1's in its structure (e.g., is a Regge recurrence of a lower lying state such as ρ, ω, π, and η) then the quarks included in these ω_1's are not to be counted in n_1. We call this modified rule the E (for "exotic") selection rule.

The special nature of the $(\omega_1{}^n)_{J=n}$ excitations is easy to see; these are exactly equivalent (in the sense of their spin, unitary spin, and parity structure) to orbital excitations in the $q\bar{q}$ orbital excitation model. Also, the addition of ω_1 pairs with spins coupled to zero corresponds to radial excitations. Thus, the nonet structuring of the normal (nonexotic) meson spectrum has been retained,[8] and these multiplets may be assigned radial and orbital excitation quantum numbers identical to those of a $q\bar{q}$ system in a potential well. Furthermore, the E selection rule permits all decays of the form "normal" → "normal" + "normal" in the $(q\bar{q})^n$ model that are allowed in the $q\bar{q}$ model. On the other hand the E rule preserves the duality criterion of the rule of Ref. 7, it allows decay of A_1 and A_2 into $\rho\pi$ (assuming the assignment we will shortly make for A_1), and it forbids decay of $\aleph$ into any pair of $(\pi, K, \bar{K}, \omega, \rho, \varphi)$ except by violation of G parity, isospin, or the E rule. The E rule also permits peripheral production of exotic mesons by exchange of the usual Regge recurrence mesons.

We may classify the quark structures possible for $\aleph$ (and its brothers in the multiplet) in terms of $q\bar{q}$ pair quantum numbers labeled by the corresponding mesons in the lowest (vector and pseudoscalar nonet) multiplets. The A_1 and A_2 would be $\rho\omega_1$ in spin-1 and -2 states, respectively; the $\epsilon(720)$ could be assigned a $\omega\omega_1$ configuration with total spin zero. The $\aleph$ $(J^P = 2^+)$ can be composed of S-wave pairs (with total $I^G = 2^+$) if it is $\rho\rho$. The other possibilities $(I^G = 1^+, 2^-)$ require internal l excitation of quark-antiquark pairs. (The degeneracy of $\aleph$ with A_2 would appear more accidental in the latter case.) Assuming the $\rho+\rho$ structure, we make other predictions.

The spin-1 state of $\rho\rho$ with $I=2$ in that case should be degenerate with A_1, and we would expect to see a relatively weak decay of this state into $\pi\rho$ interfering with A_1 decay just as in the A_2 case. There has been some evidence presented for the corresponding effect in the $K^*(1300)$ region in $K^+p \to K^+\pi\pi p$, where a narrow, positive spike on top of the broad enhancement is indicated.[9] In general, there should be many exotic states with a narrow width in this mass region.

Some of the trajectories passing through new mesons in the same multiplet as the ℵ will couple to $N\bar{N}$ states (by the E rule) and should appear in Regge-pole analyses in addition to the poles used to describe meson-baryon scattering. For example, a state with the quark structure of $\rho\rho$ or $\omega\varphi_8$ coupled to $I^G J^P = 0^+ 2^+$ may correspond to the recently reported[10] resonance near 1070 MeV. This state would generate an additional natural parity trajectory with intercept $\alpha(0)$ close to 1. Such a trajectory should be included in NN and $N\bar{N}$ elastic-scattering analyses as an additional P' term. Its contribution may be difficult to separate from that of the Pomeranchukon trajectory. In A_2 production (by pions on protons) this trajectory can be exchanged and may provide an explanation for the anomalous dependence of the A_2 production cross section upon energy.[11]

New trajectories with $I = 1$, contributing to reactions such as np and $\bar{p}p$ charge exchange, also would be expected. In our scheme we find another natural-parity trajectory as high as the A_2, and five new trajectories passing through 1^+ states; three have the G parity of the B, and two have that of A_1.

Application of the E selection rule to multiplets heavier than the $(q\bar{q})^2$ meson multiplet would lead to the proposal that there are a large number of heavy narrow resonances, some with exotic quantum numbers, many of which cannot be produced by simple pole diagrams (meson or baryon exchange). The decay modes of these mesons should be cascade in nature. The heavier ones are decoupled from baryons and cannot be produced in formation experiments using baryon-antibaryon reactions. However, at the same or similar masses are Regge recurrences of the lighter mesons which can have normal behavior; these may account for the bumps in the total cross sections in $p\bar{p}$ scattering. This would explain why the sharp peaks seen in missing-mass experiments (presumably heavy mesons with E-conserving production processes but E-inhibited decays) coincide in mass with the broad cross-section bumps.

An extension of our model to the baryons must be possible, and exotic baryons (e.g., Z^*'s) will occur. Such states are predicted in more general schemes.[7] The feature of our selection rule is that exotic baryons can occur in the same mass range as low-lying excited normal baryons and be produced via normal Regge exchanges.

The possibility that the split A_2 may result from an electromagnetic interference of two different resonances has been considered independently by G. L. Kane, M. Ross, and K. W. Lai. We would like to acknowledge extensive conversations with these authors.

Note added in proof. —An association of multiquark meson structures and the splitting of the A_2 was proposed earlier by K. E. Lassila and P. V. Ruuskanen [Phys. Rev. Letters 19, 762 (1967)]; they considered in detail the kinematic structure of the production amplitudes. However, their proposal involved a second meson with the same strong-interaction quantum numbers as the A_2, with a strong mixing between these states. In contrast, we propose an exotic meson degenerate with the A_2, which leads us to a spectroscopic scheme with many other consequences.

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[1] G. Goldhaber et al., University of California Radiation Laboratory Report No. 18894 (unpublished).

[2] M. N. Focacci et al., Phys. Rev. Letters 17, 890 (1966); H. Benz et al., Phys. Letters 28B, 233 (1968). For a recent review see B. French, in Proceedings of the Fourteenth International Conference on High Energy Physics, Vienna, Austria, 1968 (CERN Scientific Information Service, Geneva, Switzerland, 1968), p. 91.

[3] W. Beusch et al., Phys. Letters 25B, 357 (1967); D. J. Crennell et al., Phys. Rev. Letters 16, 1025 (1966), and 22, 1327 (1969).

[4] For the cases with $I = 2$ such a selection rule for decays is provided by $\mathrm{SU}(6)_W$ if, as might be expected, the ℵ belongs to a 405 representation; see D. Horn, H. J. Lipkin, and S. Meshkov, Phys. Rev. Letters 17, 1200 (1966).

[5] If the $\rho^-\pi^-$ enhancement once claimed at 1320 MeV is ever confirmed it would be a possible candidate for ℵ. See R. Vanderhagen et al., Phys. Letters 24B, 493 (1967).

[6] This scheme grew out of conversations between P. G. O. Freund and one of us (R.A.).

[7] P. G. O. Freund, J. L. Rosner, and R. Waltz, private communication from P. G. O. Freund, and to be published.

[8] Such a spectral model has been briefly discussed by R. Arnold and P. G. O. Freund, Argonne National Laboratory Report No. ANL/HEP 6910, 1969 (to be published).

[9] See Pt. 2.3.2 of B. French, Ref. 2.

[10] D. H. Miller et al., Phys. Rev. Letters 21, 1489 (1968), and Phys. Letters 28B, 51 (1968).

[11] D. R. O. Morrison, Phys. Letters 25B, 238 (1967).