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ARE THE NEW RESONANCES SUPEREXOTIC OR COLLAPSED HAN NAMBU STATES?*

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Abstract

Possible descriptions of the ψ states as unorthodox color octet states in the Han-Nambu model are discussed. Simple quark-antiquark configurations are unbound in the static colored gluon exchange model. More complicated states having indefinite numbers of quark-antiquark pairs, or "collapsed configurations" might be bound. Their radiative decays would be suppressed by the small overlap with conventional states. The unexplained spin dependence of both conventional and new meson spectra is pointed out. The ρ-π (s-wave hyperfine) mass difference is about half the ρ-f (s-p orbital) splitting, while the B-f (p-wave hyperfine) splitting is small. New particles have low-lying vectors and no trace of pseudo-scalars. A link between these spectra is suggested by the observation that precisely these features follow from adding a repulsive core to the colored gluon exchange potential in the color singlet spin triplet state which also reverses sign in the color octet states.

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We wish to point out a possible description of the ψ states[1] in the Han-Nambu model[2] as color-octet vector mesons which are not simple quark-antiquark states but have a more complicated structure. Some possibilities are an "exotic" configuration involving two or more quark-antiquark pairs or a "superexotic" configuration which is a mixture of states containing different numbers of quark-antiquark pairs. Such wave functions are suggested by simple models[3)4] of interacting colored quarks originally introduced in the framework of a three-triplet model to explain the saturation properties of the observed hadron spectrum. Complicated wave functions are also suggested by the experimental absence of simple radiative decays of the ψ states to ordinary hadrons.

In models with heavy quarks bound by strong attractive forces, the Yukawa interaction produced in the static approximation by exchange of an octet of colored vector gluons leads naturally to binding of quark-antiquark and three-quark configurations and a saturation which prevents the binding of additional quarks and antiquarks. The essential feature of this interaction which prevents an additional quark from being attracted by a bound quark-antiquark pair is that the quark-antiquark interaction is attractive in the color singlet state but is repulsive in the color octet state. Therefore in the static approximation this model has no bound states of quark-antiquark pairs in color octet configurations. Any low-lying color octet states would have to be in more complicated configurations.

We now note that such more complicated configurations provide a natural answer to the question of why the ψ states are so narrow. All simple quark-antiquark models for the ψ face the difficulty of explaining why the strong electromagnetic coupling to the photon necessary to describe the observed production of these states does not give rise to a large width for electromagnetic decays with the emission of a single photon. The observed width of 1 MeV for the decay $\omega \to \pi\gamma$ gives a measure for the expected width of such a single photon decay, and the ψ widths for this mode are smaller by several orders of magnitude. The production cross section for the ψ in e^+e^- annihilation is comparable to ω production. Thus if this production is electromagnetic and not due to a new weak interaction, the magnitude of the matrix element of the electromagnetic current between the vacuum and the ψ is comparable to that between the vacuum and the ω.

$$\langle 0|J_{em}|\psi\rangle \approx \langle 0|J_{em}|\omega\rangle. \tag{1}$$

There can therefore be no symmetry or selection rule suppressing the matrix element of the electromagnetic current between the resonant state and a state H_V of one or more hadrons having the same eigenvalues as the vacuum for all quantities conserved in electromagnetic interactions.

$$\langle 0|J_{em}|\psi\rangle \neq 0 \Rightarrow \langle H_V|J_{em}|\psi\rangle \neq 0. \tag{2}$$

Yet the experimental narrow width of the ψ tells us that

$$\langle H_V|J_{em}|\psi\rangle << \langle \pi|J_{em}|\omega\rangle \tag{3}$$

The only possible explanation is that the ψ resonances have a very different structure from all possible states of lower mass so that the overlap of the resonance wave function with any possible final state is small. Models in which the new resonances are bound states of a charmed[5)] quark-antiquark pair meet this criterion only if there are no possible final states with appreciable phase space consisting of charmed quarks. This requires that the pseudoscalar mesons made from charmed quark-antiquark pairs should not lie much lower than the second vector state $\psi'(3700)$, in contrast to the case of uncharmed quarks. Furthermore, there cannot be mixing of charmed quark states into the low-lying pseudoscalar mesons as this would allow decays to the η or X^0 through the charmed component. Such an "exact ideal mixing angle" is inconsistent with the kind of non-ideal mixing found in the uncharmed pseudoscalars.

In the Han-Nambu model the electromagnetic current contains a color octet component which can excite color octet vector meson states. However a quark-antiquark pair in a color octet state with a wave function very similar to those of the ordinary color singlet mesons has an electromagnetic transition matrix element between such a color octet state and the low lying pseudoscalar mesons of order unity. There is no way to forbid any such Han-Nambu quark-antiquark vector meson which has a large coupling to the photon from decaying into a pseudoscalar and a photon with a width comparable to $\omega \to \pi\gamma$. This difficulty is avoided in the particular version of the Han-Nambu model discussed in I with colored gluon exchange forces because there are no bound color octet states in the quark-antiquark system.

We now examine all other color octet configurations with zero baryon number in this model in the static approximation with the Yukawa potential. We first consider states of two quarks and two antiquarks.

Eq. (3) and Table 1 of I show that any color octet state has a higher mass than that of the diquark-antidiquark system and that the diquark-antidiquark interaction is repulsive in color octet states. Furthermore all color octet states with two or more quark-antiquark pairs can dissociate into a diquark, an antidiquark and a number of ordinary color singlet mesons. Thus there are no color octet bound states at all in this static approximation.

However, we have neglected higher order effects, such as the creation and annihilation of quark-antiquark pairs and the emission or absorption of vector gluons. These interactions might overcome the repulsive Yukawa force in color octet states. The importance of pair creation and annihilation interactions would suggest that the bound states be coherent linear combinations of states containing many quark-antiquark pairs. Thus if any color octet states are bound they must have a completely different structure from the low-lying color singlet states. Unfortunately there is no simple way to calculate quantitative properties of such states.

This argument can also be stated in the framework of other models than the simple nonrelativistic constituent quark model. In the quark-parton model[6)] with valence quarks in a sea of quark-antiquark pairs, the sea in a color octet state could be very different from the sea in a color singlet state. This would naturally occur if the sea is produced by the constant emission and absorption of a color octet of vector gluons which create quark-antiquark pairs in the color octet state but not in the color singlet state.

As an example, consider a color octet state in which the valence quarks are in a color singlet state and the color excitation is all in the sea which is a color octet. The wave function for such a hadron state can be written

$$|H\rangle = |V_H\rangle \times |S_H\rangle \tag{4}$$

where V denotes the wave function of the valence quarks and S the wave function of the sea. In this factorized approximation the seas for the ω and π mesons are the same and the $\omega \to \pi\gamma$ decay is a transition involving only the valence quarks

$$\langle\pi|J_{em}|\omega\rangle = \langle V_\pi|J_{em}|V_\omega\rangle \times \langle S_\pi|S_\omega\rangle \tag{5a}$$

$$\langle S_\pi|S_\omega\rangle = 1 \tag{5b}$$

If the ψ has color singlet valence quarks and a color octet sea the electromagnetic transition matrix element to a color singlet hadron state having the factorized form (4) is given by

$$\langle H|J_{em}|\psi\rangle = \langle V_H|V_\psi\rangle \times \langle S_H|J_{em}|S_\psi\rangle \tag{6}$$

The electromagnetic current must act on the sea part of the wave function in order to produce a transition from a color octet to a color singlet state. Comparison of eqs. (5) and (6) shows that the two matrix elements have a completely different structure and therefore the ψ transition (6) could be much smaller than the ω-decay (5a) in agreement with the observed inequality (3). In fact if the sea has angular momentum zero in both states as is usually assumed the matrix element (6) vanishes for real photons by angular momentum conservation because it is a $0 \to 0$ transition

$$\langle S_H \gamma | S_\psi \rangle = 0 \qquad (7)$$

Similar qualitative arguments can be given in the context of "bag" models[7] of quark confinement. It is quite possible that color octets states in the bag would have drastically different properties from the color singlet states and that electromagnetic transition matrix elements between the two types of states would be very small.

Although the model of superexotic colored quark configurations in the Han-Nambu model gives a natural explanation for the narrowness of the states, the absence of any detailed model and a large freedom in choice of wave functions gives it very little predictive power. However, symmetry properties may enable the prediction of branching ratio to different final states. These might furnish a test of the approach.

Another possibility suggested by the colored-quark octet-gluon model is to introduce a very short range repulsive core into the attractive quark-antiquark potential binding the color singlet state. If this potential has the same color dependence as the attractive potential, it has the opposite sign in the color octet state and becomes a very short range attractive potential surrounded by a repulsive potential barrier. The bound states in this potential could well have a very different wave function from the color singlet states and inhibit the troublesome matrix element (3). Such "collapsed" states have been suggested for complex nuclei[8].

So far this is very ad hoc. But the assumption that such a repulsive core exists only in the triplet spin state leads to explanations not only of some properties but also of some unexplained features of the normal hadron spectrum.

The spin splittings in the meson spectrum are very peculiar in the non-relativistic quark model. The ρ-π mass difference is large and is the same order as the ρ-f mass splitting while the B meson mass is very nearly the same as that of the f. In the language of atomic physics the $\rho\pi$ difference is the "hyperfine splitting" in the lowest s-state of the bound system and is about half of the π-f mass difference which is the orbital excitation energy of thellowest p-state. The B-f difference is the hyperfine splitting in the p-state and is very small. In conventional quark model descriptions the spin splitting is due to a spin-spin interaction term which is introduced ad hoc with a magnitude determined by an adjustable parameter. There is no a priori reason for this parameter to be of the same order as the orbital excitation energy for s-wave spin splittings and to be nearly zero for p-wave spin splittings.

A repulsive core in the triplet spin state gives this qualitative level structure. If it is very short range it does not affect the p-wave and its effect on the s-wave forces the wave function to be very small near the origin. The energy of the ^3S state is then pushed up by an amount characteristic of the orbital excitation energy and independent of the strength of the spin-dependent repulsive potential. For a rough quantitative estimate of this effect, we note that the radial wave function of the lowest s-state in a harmonic oscillator potential with a repulsive

core must vanish near the origin and have no nodes and thus could be very similar to the radial wave function of the lowest p-state. We take the p-wave harmonic oscillator radial wave function combined with s-wave angular dependence as an approximation to the s-wave with repulsive core and calculate the expectation value of the oscillator Hamiltonian. With unperturbed oscillator wave functions for the spin-singlet s-state and both p-states, the energy spectrum obtained is

$$E_\pi\ (^1S\text{-unperturbed}) = (3/2)\hbar\omega$$

$$E_\rho\ (^3S\text{ p-wave radial with S-wave angular dependence}) = 11/6\ \hbar\omega$$

$$E_{f^o} = E_B\ (^3P\text{ and }^1P\text{ - unperturbed}) = (5/2)\ \hbar\omega$$

Thus a repulsive core in the spin triplet color singlet state which reverses sign in the color octet state gives the following desirable features:

1) It places the ρ about midway between the π and f
2) It leaves the B and f^o degenerate
3) It gives bound states for color octet vector mesons which have very different wave functions from the color singlet states.
4) It does not bind pseudoscalar color octet states and leaves the vector mesons as the lowest color octet states.

We now consider possible experimental tests of the superexotic colored approach. Rather than examining detailed models we examine symmetry arguments motivated by the colored superexotic model but having a more general validity.

We first consider the classification of the ψ states in the conventional SU(3). There are two obvious choices. Either the two states are both SU(3) singlets or they are two members of a nonet like the conventional vector mesons. The singlet classification is consistent with the charm description, the nonet classification with color but the question of whether the ψ's are singlets or members of a nonet is model independent and interesting in its own right.

If the ψ's are two states in a nonet there must also be a third state having a zero charge and hypercharge. The natural classification in a color model is to assume ideal mixing in ordinary SU(3) as in the low-lying vector nonet and to give the two observed states the quantum numbers of the ω and ϕ . A third state yet unobserved must then exist with the quantum numbers of the ρ. We denote the three states by ψ_ω , ψ_ρ and ψ_ϕ respectively. In the Han-Nambu model only ψ_ω and ψ_ϕ are produced by electron-positron annihilation and have a lepton pair decay mode. Because the color octet component of the electromagnetic current is a singlet in the ordinary SU(3) and is a isospin scalar the isovector color octet ψ_ρ has no direct coupling to the photon.

If the ψ's are really in an SU(3) nonet and ψ_ρ is not coupled to the photon as suggested by the Han-Nambu model the ψ_ρ should be in a mass range near that of the ψ_ω around 3.1 GeV and should be observed in the final states of the decay of the higher ψ_ϕ . For example in the decay

$$\psi_\phi(3700) \to \psi_\rho + \pi \qquad (8a)$$

This decay would be expected to have a width comparable to that of the observed decay

$$\psi_\phi(3700) \to \psi_\omega(3100) + 2\pi \qquad (8b)$$

The two decays (8) are directly analogous to the transitions

$$\phi \to \rho + \pi \qquad (9a)$$

$$\phi \to \omega + 2\pi \qquad (9b)$$

In all these decays a strange quark-antiquark pair disappears into a final state containing no strange quarks, a process forbidden by Zweig's rule. The observed rate of the decay (8b) is consistent with the observed decay (9a) and the total width of the ψ is consistent with the existence of an additional channel (8a) with a comparable width. Direct detection of the decay (8a) is more difficult than that of (8b) because the absence of the lepton pair decay mode for ψ_ρ does not give an easily detected signature like the ψ_ω . The simplest way to search for the decay (8a) is to examine the pion spectrum to look for a peak characteristic of a quasi-two-body decay mode. This of course will be done in any case regardless of the predictions of any theoretical model.

An important test of the color octet classification would seem to be possible G-parity violation in decays, since the color octet state cannot decay to color singlet states via G- conserving strong interactions. However, only very small G violations are predicted by the simplest model for non-photon electromagnetic decays, namely the model of emission and reabsorption of a photon by a quark-antiquark pair. Since the quantum numbers of a quark cannot change in the emission and absorption of a photon, the strange quarks in the ψ_ϕ remain strange and G-parity is conserved in the decay

$$\psi_\phi \to (\lambda\bar{\lambda})_{\text{color singlet}} \qquad (10a)$$

For the states ϕ_ω and ϕ_ρ which are mixtures of p-type and n-type quark-antiquark pairs, the relative magnitudes of the $p\bar{p}$ and $n\bar{n}$ components change during the emission and absorption of the photon, because of the differences in the quark charges. This produces some G-parity violation.

$$(p\bar{p} + n\bar{n})_{\text{color octet}} \to (2p\bar{p}+n\bar{n})_{\text{color singlet}} = \frac{3}{2}(p\bar{p}+n\bar{n}) + \frac{1}{2}(p\bar{p}-n\bar{n})$$

However, this is a small effect with a 9:1 ratio favoring the G-conserving component of the wave function over the G-violating component.

Further symmetry tests are discussed in detail elsewhere[9].

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