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Glueballs, Multiquark States and the OZI Rule

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ABSTRACT

New signatures for detection of non-quarkonium mesons are considered, including $K^+K^+\pi^+\pi^-$ and $K_sK_s\pi^+\pi^+$ decays for states where K^+K^+ and K^+K^{*+} decays are forbidden, and A-dependence of S^* and δ production on nuclei by kaon beams. Analysis of OZI rule shows that only selection rules forbidding hairpin diagrams are valid and that $\phi\phi$ production by pion beams is not a serious OZI violation indicating presence of glueballs.

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Glueballs and exotic four quark states can be identified and distinguished from conventional $q\bar{q}$ mesons only by unambiguous signatures like exotic flavor quantum numbers and decay modes forbidden by OZI [1-11] and flavor symmetry [12-13] selection rules. This paper considers new candidates and new possible signatures for four quark states and analyzes the application and validity of the OZI rule [4--11] with particular emphasis on inconsistencies and confusion in its use to identify glueballs.

No exotic states have yet been found and QCD-motivated models [14,15] predict that the lowest lying four-quark states with only uds flavors do not have exotic quantum numbers. With four flavors these models predict low-lying charmed-strange exotics [15,17] but none have yet been found. Exotic states at higher mass are expected to be very wide and not easily detected because they have many open decay channels and decay easily by breakup into two $q\bar{q}$ mesons.

We suggest a search for doubly-charged doubly-strange mesons with quark configurations like $(uu\bar{s}\bar{s})$ with J^{PG} quantum numbers for which the K^+K^+ and K^+K^{*+} decay modes are forbidden or suppressed. The masses of such multiquark states are not easily calculated in any reliable model, because they involve orbital excitations. But the phase space for allowed decays may be relatively small even if the masses are in the 2 GeV region, because the final states of three or four mesons must contain at least two kaons and have finite orbital angular momenta. They may be narrow enough to show up as detectable peaks in the $KK\pi\pi$ spectrum.

J^{PG} selection rules determine the quantum numbers of the most promising candidates. The relevant G parity is G_V parity, defined with V spin instead of isospin. G_V interchanges $\underline{u}$ quarks and $\bar{s}$ antiquarks, and $(uu\bar{s}\bar{s})$ states are eigenstates of G_V. G_V conservation has been tested experimentally in the charmonium spectrum and also shown to be valid on theoretical grounds, even in the presence of large SU(3) symmetry breaking [13]. The K^+K^+ state is even under G_V and the K^+K^{*+} state is odd. Thus one of these decay modes is always forbidden for any G_V eigenstate. Bose statistics forbids odd-J and odd-P states for the K^+K^+ system, and angular momentum and parity forbid $J^P = 0^+$ for K^+K^{*+}.

The lowest lying odd-parity and even-G_V $(uu\bar{s}\bar{s})$ states have orbital angular momentum L=1 and quark spin S=1 coupled to $J^{PG} = 0^{-+}$, 1^{-+} and 2^{-+}. Both K^+K^+ and K^+K^{*+} decay modes are forbidden. The lowest allowed quasi-two-body channels are p-wave decays into $K_V^*K_V^*$, KQ, KK_S^* and KK_T^*, where the subscripts S, V and T denote scalar, vector and tensor respectively. The three-body $KK\pi$ is allowed, but may be suppressed by centrifugal barriers in the 2^{-+} and 1^{-+} states, which have one and two relative d-waves respectively.

A $J^{PG} = 3^{--}$ state with L=1, S=2 has the K^+K^+ decay forbidden by bose statistics and also by G_V conservation. The K^+K^{*+} decay is allowed but might be suppressed by the f-wave centrifugal barrier and low overlaps for breakup due to spin recouplings and the creation of two units of orbital angular momentum. The s-wave $K_V^*K_T^*$ decay is allowed but has a high threshold.

A $J^{PG} = 0^{+-}$ state with L=2, S=2 has the K^+K^+ decay forbidden by G_V conservation, and all $KK\pi$ decays as well as K^+K^{*+} forbidden by angular momentum and parity selection rules. This state cannot decay into less than four pseudoscalar mesons $(KK\pi\pi)$. Its lowest quasi-two-body decays are KQ and $K_V^*K_T^*$ p-waves to $(KK\pi\pi)$ final states.

Their most striking signatures are the obviously exotic doubly-charged $K^+K^+\pi^+\pi^-$ and $K_SK_S\pi^+\pi^+$ decays. The $K^+K^+\pi^+\pi^-$ mode also has an unambiguous double-strangeness signature if there is good separation of kaons and pions. The strangeness is not established in the $K_s K_s \pi^+ \pi^+$ mode without additional information.

Another kind of four-quark state, a loosely bound deuteron-like $K\bar{K}$ state, has been predicted by Weinstein and Isgur [18] from a simple potential model. They claim that the S^* and δ scalar mesons are indeed such states. Since the validity of the potential model has been questioned for multiquark states [19,20], we show here that their predictions follow from general properties of the two-meson system and are independent of the details of their model calculation. We then investigate possible experimental tests of this picture.

The force between two color-singet hadrons has been shown to be dominated by the short-range hyperfine interaction [17], while the color electric forces are negligible. A gain in potential energy of about 200 MeV results from bringing two separated kaons together to make a four-particle alpha-particle-like cluster and recoupling colors and spins to minimize the energy [16]. The alpha-particle-like cluster is not bound because this potential energy is not sufficient to overcome the kinetic energy required to localize the two mesons. Weinstein and Isgur [18] investigated more complicated spatial configurations in their potential model and found binding only in deuteron-like configurations of the $K\bar{K}$ system and nowhere else.

For a more general investigation of deuteron-like bound states, we describe meson-meson phenomenology at low energies by a nonrelativistic Schroedinger equation with the hyperfine interaction replaced by a short range attractive potential whose strength is inversely proportional to the product of the quark masses [14]. Problems of color polarization or long range color correlations [19,20] are avoided because the only interaction between the mesons has a very short range. For this well-known two-body problem a bound state exists if the strength of the potential exceeds a critical value. For two pseudoscalar mesons of mass M, interacting via a square-well potential of range $\underline{a}$ and depth (U/m_1m_2), where m_1 and m_2 are the masses of the constituent quarks in the meson, the condition for existence of a bound state is

$$MU/m_1m_2 \geq \pi^2\hbar^2/4a^2 \qquad (1)$$

The most likely candidate for a bound state is the two-meson system for which the left hand side of the inequality (1) has its maximum value. Substituting the experimental meson masses for M and the conventional constituent quark masses for m_1 and m_2 shows that the maximum occurs for the two-kaon system. If the two-kaon system is barely bound, no other system will satisfy the inequality (1) and there will be no other bound states. For heavier systems the quark mass is too heavy and the hyperfine interaction too small to produce binding; for lighter systems involving pions, the small pion mass makes the kinetic energy of localization too high. This result is completely general and independent of the choice of the square well potential or of the values of the parameters, except for the general assumption that there is very weak or no binding. A relation similar to (2) holds for any short range potential, with other strength and range parameters corresponding to U and a.

This result can also be seen by substituting for M in eq. (1) the simple meson mass formula [21-24],

$$M = 2m_q - (3/4)(M_{K^*} - M_K)(m_u m_s/m_q^2) \qquad (2a)$$

where we have assumed equal quark masses m_q for simplicity and used the experimental K and K^* masses to define the strength of the hyperfine contribution to the meson mass. Then

$$(2/m_q) - (3/4)(M_K^* - M_K)(m_u m_s/m_q^4)U \geq \pi^2\hbar^2/4a^2 \qquad (2b)$$

The left hand side of (2b) is maximized when

$$m_q^3 = (3/2)(M_K^* - M_K)m_u m_s \qquad (3a)$$

For $M_K^* - M_K = 400$ MeV, $m_u = 330$ MeV and $m_s = 510$ MeV, [25] this gives

$$m_q = 465 \text{ MeV} \qquad (3b)$$

This value between m_u and m_s again shows that the maximum is for the two-kaon system.

This deuteron-like structure could be tested experimentally by measurement of the sizes or form factors of these mesons. Effects of breakup of these loosely bound states in passing through nuclear matter might be seen in comparing the A-dependence of S^* and δ production on finite nuclei with that of normal quarkonium states; e.g by comparing the A dependences of the S^* and δ peaks respectively in the $\pi\pi$ and $\eta\pi$ spectra with the corresponding quarkonium peaks from ρ, f and A2 production and decay. Reactions analogous to deuteron stripping on nuclei might occur with the $\bar{K}$ stripped from the bound state by the nucleus, creating a hypernucleus and a residual kaon.

We now clarify the application of the OZI rule to distinguish between four-quark, glueball and ordinary quarkonium states. Confusion arises because two different versions of OZI are always quoted as <u>the</u> OZI rule. The successful version of OZI which is in remarkable agreement with experiment and has a hand-waving QCD justification refers only to "hairpin-type" diagrams in which two quark lines <u>from a single hadron</u> come together to form a hairpin-like loop disconnected from the remainder of the diagram, [5,6];

e.g. the production and decays of strangeonium or charmonium mesons when there are no other strange or charmed quarks present in this reaction.

Well known examples are the decays

$$\phi \longrightarrow \rho + \pi \tag{4a}$$

$$\psi \longrightarrow \text{hadrons} \tag{4b}$$

and the reactions

$$\pi^- + p \longrightarrow \phi + n \tag{5a}$$

$$\pi^- + p \longrightarrow M^o + n \longrightarrow \phi + \phi + n \tag{5b}$$

where M^o denotes any ideally-mixed quarkonium state.

The naive topological version of OZI in which <u>all</u> "disconnected diagrams" are forbidden is still used {10,11}, even though it is now in strong disagreement with experiment {6,7} and has no theoretical justification from QCD. There is no experimental nor theoretical reason to forbid processes described by non-hairpin disconnected diagrams in which the smallest disconnected piece has quark lines from two or more hadrons. Such diagrams also describe the strongest processes known; namely elastic and diffraction scattering and pion exchange {5}. For example, a reaction of the type (5b) which does not go through an intermediate meson resonance,

$$\pi^- + p \longrightarrow \phi + \phi + n \tag{6a}$$

is not described by a hairpin diagram. It is related by crossing to the reaction

$$\phi + n \longrightarrow \phi + \pi^- + p. \tag{6b}$$

This is just elastic ϕ-nucleon scattering with additional pion production, possibly by diffractive excitation of a nucleon resonance. There is no reason to believe that this process (6b) is forbidden.

The dominant decay mode of the ψ'(3700) particle,

$$\psi' \longrightarrow \psi + 2\pi \tag{7a}$$

is described by a non-hairpin diagram containing two disconnected pieces each with two hadron lines and is several orders of magnitude stronger than all other hadronic ψ' decays which are described by OZI forbidden hairpin diagrams. It is related by crossing to the diffractive excitation of the ψ' in $\pi\psi$ scattering.

$$\psi + \pi \longrightarrow \psi' + \pi \qquad (7b)$$

The reactions (6a) and (7a) are described by non-hairpin diagrams called "crossed pomeron diagrams" in ref. 5, since they are related by crossing to reactions like (6b) and (7b) which can take place via pomeron exchange. In QCD the arguments for suppression of hairpin diagrams do not apply to these processes which can go easily via two gluon exchange. There is no experimental evidence for suppression of the crossed pomeron diagrams comparable to that of hairpin diagrams. These "crossed pomeron" processes have either a much smaller suppression as in the reaction (7a) or no suppression at all.

A recent experimental test of OZI in diffractive photoproduction of three-meson states [7] shows that "OZI-forbidden" $\phi\pi\pi$ photoproduction is not appreciably suppressed relative to other "OZI-allowed" processes. We present a broken-SU(3) analysis of their data and show that the contributions of crossed pomeron processes are comparable to those from allowed connected diagrams.

The transition of a photon to the $\phi\pi\pi$ three-meson state

$$\gamma \longrightarrow \phi + \pi^+ + \pi^- \qquad (8a)$$

resembles the ψ' decay (7a) and is related by crossing to ϕ photoproduction on a pion target.

$$\gamma + \pi^- \longrightarrow \phi + \pi^- \qquad (8b)$$

The transition (8a) is forbidden by the naive OZI selection rule which allows only connected diagrams,

$$\langle \phi\pi^+\pi^- | C | \gamma \rangle = 0 \tag{9}$$

where $\langle VPP | C | \gamma \rangle$ denotes the transition matrix element for VPP photoproduction via connected diagrams. The pion photoproduction process (8b) is described by a "disconnected" diagram in which the ϕ-component of the photon is scattered diffractively on the pion target by pomeron exchange. The transition (8a) is thus a disconnected crossed pomeron process analogous to the reactions (7a) and (6a).

An extremely useful test of naive OZI is obtained from (9) by the SU(3) transformation which interchanges d and s quarks (180° U-spin rotation),

$$\langle V_d K^+K^- | C | \gamma \rangle = 0 \tag{10a}$$

where V_d denotes a neutral vector meson with the constituents $d\bar{d}$ which is a linear combination of ρ^0 and ω,

$$V_d = \{1/\sqrt{2}\}\{\omega - \rho^0\} \tag{10b}$$

A relation between physically observable processes is obtained from this selection rule by substituting eq. (10b) into eq. (10a),

$$\langle \rho K^+K^- | C | \gamma \rangle - \langle \omega K^+K^- | C | \gamma \rangle = 0 \tag{10c}$$

The experimental results show strong disagreement with both relations (9) and (10c). The "OZI-allowed" ϕK^+K^- photoproduction is at least an order of magnitude smaller than the "OZI-forbidden" $\phi\pi^+\pi^-$ photoproduction {7}.

$$\phi K^+K^- / \phi\pi^+\pi^- = 0.05 \pm 0.06 \tag{11a}$$

where VPP denotes the photoproduction cross section for the VPP final state. Comparison of corresponding processes of ϕ and ω production, suggested {8} as a better test, gives

$$\phi\pi^+\pi^- / \omega\pi^+\pi^- = 0.097 \pm 0.019 \tag{11b}$$

Here the forbidden process is an order of magnitude smaller than the allowed process, but is considerably larger than expected from similar comparisons elsewhere; e.g. the 2% suppression factor found in the comparison of the reaction (5a) with the corresponding ω production. Both results (11) can be explained by a suppression of one order of magnitude (a factor of 3 or 4 in amplitude) for the production of an additional strange quark pair, with no OZI suppression at all.

Effects of strangeness suppression factors were minimized by comparing states with the same number of strange quarks all decaying to the same final state of two kaons and two pions.

$$\phi\pi^+\pi^-/K^{*0}K^\pm\pi^\mp = 0.35 \pm 0.07 \quad (12a)$$

$$\phi\pi^+\pi^-/\rho K^+K^- = 0.68 \pm 0.14 \quad (12b)$$

$$\phi\pi^+\pi^-/\omega K^+K^- = 2.02 \pm 0.7. \quad (12c)$$

Again there is no suppression of the "OZI-forbidden" process relative to allowed processes.

Complications from strangeness suppression effects are avoided completely by using the relation (10c),

$$\{(\rho K^+K^- - \omega K^+K^-)/\rho K^+K^-\} = 0.65 \pm 0.10 \neq 0 \quad (13)$$

Again there is no OZI suppression.

We now show that the crossed pomeron contributions provide a consistent explanation of both violations (12b) and (13) of naive OZI. In the SU(3) symmetry limit there are only three independent couplings for $\gamma \longrightarrow VPP$ transitions if hairpin diagrams are forbidden. These are reduced to two by the naive OZI rule which imposes the constraint (9). We therefore express all the photoproduction cross sections appearing in the experimental relations (11-13) in terms of three parameters. We choose a convenient description in which crossed-pomeron contributions forbidden by naive OZI are all proportional to one parameter denoted by P, while the connected diagram contributions allowed by naive OZI all depend only upon the two other parameters denoted by D and X and defined by the relations

$$\sqrt{D} \equiv \langle V_u K^+K^- | C | \gamma_u \rangle = \langle V_u \pi^+\pi^- | C | \gamma_u \rangle = \langle V_d \pi^+\pi^- | C | \gamma_d \rangle =$$
$$= \langle \phi K^+K^- | C | \gamma_s \rangle = \langle K^{*o}K^-\pi^+ | C | \gamma_s \rangle + \langle K^{*o}K^-\pi^+ | C | \gamma_d \rangle \qquad (14a)$$

$$\sqrt{X} \equiv \langle V_u K^+K^- | C | \gamma_s \rangle = \langle V_u \pi^+\pi^- | C | \gamma_d \rangle = \langle V_d \pi^+\pi^- | C | \gamma_u \rangle =$$
$$= \langle \phi K^+K^- | C | \gamma_u \rangle = \langle K^{*o}K^-\pi^+ | C | \gamma_u \rangle \qquad (14b)$$

where γ_u, γ_d and γ_s denote the $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$ components of the photon normalized so that

$$\langle VPP | C | \gamma \rangle = 2\langle VPP | C | \gamma_u \rangle - \langle VPP | C | \gamma_d \rangle - \langle VPP | C | \gamma_s \rangle \qquad (14c)$$

We assume that the three contributions P, D and X are incoherent since they probably populate different regions of the three-body phase space. To correct for symmetry-breaking we introduce two strangeness suppression factors denoted by S_ϕ and S_G for diagrams containing strange quark pairs produced respectively from γ_s and by gluons from the vacuum. Then

$$\phi\pi^+\pi^- = 2PS_\phi \qquad (15a)$$

$$\omega K^+K^- = \{2DS_G + (1/2)XS_\phi\} + PS_G \qquad (15b)$$

$$\rho K^+K^- = \{2DS_G + (1/2)XS_\phi\} + 9PS_G \qquad (15c)$$

$$\phi K^+K^- = DS_\phi S_G + 4XS_G^2 + PS_G^2 \qquad (16a)$$

$$\omega\pi^+\pi^- = (1/2)D + (1/2)X + P \qquad (16b)$$

$$K^{*o}K^-\pi^+ + \overline{K^{*o}}K^+\pi^- = \{8X + (9/2)D\}S_G \qquad (16c)$$

The same connected contribution $\{2DS_G + (1/2)XS_\phi\}$ is seen to appear in ωK^+K^- and ρK^+K^- as expected from (10c). The experimental ratio (13) shows that this connected contribution is of the same order as the crossed pomeron contributions PS_G and $9PS_G$.

$$\{2DS_G + (1/2)XS_\phi\}/PS_G = \{9-(\rho K^+K^-/\omega K^+K^-)\}/\{(\rho K^+K^-/\omega K^+K^-)-1\} \cong 3 \quad (17a)$$

This result, which is completely independent of strangeness suppression factors, confirms that crossed pomeron contributions are not strongly suppressed and that the naive OZI rule is violated.

From eqs. (12) and (15),

$$S_\phi/S_G = 4\phi\pi^+\pi^-/(\rho K^+K^- - \omega K^+K^-) \cong 4 \quad (17b)$$

Substituting the results (17) into eqs. (14-16), we obtain

$$\{\phi K^+K^- \cdot \omega\pi^+\pi^-\}/\{\phi\pi^+\pi^-\}^2 \approx 49/256 \quad (18a)$$

$$(2/3) \leq \phi\pi^+\pi^-/K^{*0}K^\pm\pi^\mp \leq (32/27) \quad (18b)$$

Comparison of these predictions (18) with the experimental results (11) and (5a) shows reasonable agreement. Discrepancies of less than a factor of two are certainly acceptable in such a crude model and confirm the absence of large OZI suppression of crossed pomeron processes.

The experimental observation of the reaction (6a) is thus adequately explained as a crossed pomeron process without assuming new kinds of particles [10,11], unless it proceeds via an intermediate meson resonance as in the reaction (5b). A quarkonium resonance cannot be produced and detected this way without a forbidden hairpin diagram. However, the state must be a resonance, and not just a broad enhancement, to be considered as evidence for a new kind of object. Furthermore, a trivial type of OZI violation occurs whenever a meson resonance which is not ideally mixed occurs in an intermediate state; e.g. the η or its radial excitations. The reaction (5b) can occur via such a resonance, with the production via the $u\bar{u}$ or $d\bar{d}$ component and decay via the $s\bar{s}$ component.

A crucial test for identification of any resonance with mass above 2 GeV where many decay channels are open is to observe other decay modes. A glueball which decays in the $\phi\phi$ mode also decays with equal amplitudes into a pair of any of the other eight states in the vector nonet, while the $K^*\bar{K}$ decay mode is forbidden {12}. Decays of the same object into $\phi\phi$ and $\rho\rho$ or $\omega\omega$ together with the absence of the $K^*\bar{K}$ decay mode have been pointed out as striking signatures for glueball candidates {13}. A tensor four-quark ($ss\bar{s}\bar{s}$) state would decay by s-wave breakup into $\phi\phi$ and not into any other vector meson pair.

For states like the $\theta(1700)$ {26} between the $K^*\bar{K}$ and $\phi\phi$ thresholds the absence of the $K^*\bar{K}$ decay mode provides a very sensitive test. This decay mode is allowed for corresponding quarkonium states. In the case of the $\theta(1700)$, the absence of the $\pi\pi$ decay mode which is related by SU(3) to the observed $K\bar{K}$ decay mode has been taken as evidence for a four-quark structure rather than a glueball. Since the $\theta(1700)$ has been observed together with the quarkonium f' in the $K\bar{K}$ decay mode, interesting information is obtainable from a direct comparison of the two states in the $K^*\bar{K}$ decay mode. The $f' \to K^*\bar{K}$ decay is allowed and can be predicted from SU(3) from the observed $A2 \to \rho\pi$ decay. A tensor four-quark state should be seen in this mode, but there should be no signal from the θ if it is a glueball or if it is a scalar meson rather than a tensor meson.

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