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Metastable exotic mesons

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A diquark-antidiquark model is proposed to account for the narrow mesonic states reported in the 1.4-to-2.0-GeV mass region, and also for the higher-lying broad baryonium states. Several experimental tests are suggested.

I. INTRODUCTION

Over the last few years, there has been much interest concerning the existence of an ever increasing number of hadronic states[1,2] close to and above the nucleon-antinucleon threshold. These states are characterized by relatively narrow widths and large coupling to the nucleon-antinucleon system. The most appealing explanation of these states is that they are the so-called baryonium states, whose existence is required by dual models.[3,4] In terms of the constituent-quark model, they are thought to consist of two quarks (forming a diquark[5]) and two antiquarks (forming an antidiquark). Such states are expected in many quark models, for example the MIT bag model of Jaffe *et al.*[6,7]

In the quark model however, there is a problem with regard to the stability of these states. Naively one might expect they would be broad since the quarks and antiquarks would just rearrange themselves into two mesons. This is indeed the case for at least some of these states in the bag model, the ϵ and δ mesons having been suggested[7] as such objects. In order to achieve narrow widths, attempts have been made to forbid this rearrangement by assuming that the states have high angular momenta[8,9]; the rearrangement process is then inhibited due to the angular momentum barrier between the diquark and the antidiquark. A consequence of this explanation would therefore be that the low-lying diquark-antidiquark states (those with low angular momenta) would be relatively broad.

Recently, several narrow low-mass states below the nucleon-antinucleon threshold have been reported. Two narrow states at 1500 and 1812 MeV have been observed by groups[10-13] working in e^+e^- annihilation at Adone. Of course, there is no evidence that these states have anything to do with baryonium. However, their rather narrow widths argue against their being regular mesonic states. Three further states, coupled to the $\bar{p}p$ channel, have been deduced from the $\bar{p}p$-annihilation-at-rest experiment of Pavlopoulos *et al.*[14] They observe $\bar{p}p \to X\gamma$, and see three discrete lines in the photon spectrum corresponding to masses 1395, 1646, and 1684 MeV for X. The widths of these lines are consistent with the experimental resolution (15 MeV).

One should certainly be wary of these states at this stage since all of them are less than 3-standard-deviation effects. Much experimental work clearly needs to be done. Resolution and statistics need to be greatly improved, and it is by no means certain that all of the narrow peaks reported in the literature, whether below or above the nucleon-antinucleon threshold, correspond to real resonances. Indeed, for some of the higher-mass states, there already exist contradictory experimental results. With some reservation therefore about the experimental situation, what we shall do in this paper is to examine whether it is possible to fit into the diquark-antidiquark scheme the various observed narrow states, including the low-mass states observed by the Adone groups and by Pavlopoulos *et al.*

If these low-mass states correspond to the low-lying levels in a diquark-antidiquark scheme, their spins are expected to be small (say $J \lesssim 2$). The Adone states of course have $J^{PC} = 1^{--}$. Thus if these states do belong to this scheme, it implies that their stability must come from some means other than high orbital angular momentum (invoked for the higher masses). The origin of this stability is as yet unknown, although several popular theoretical models all seem to indicate the possibility of the existence of narrow states. In the string model[1,15] for example, a diquark-antidiquark system [Fig. 1(a)] clearly wants to fall apart into a baryon and an antibaryon by breaking the central string [Fig. 1(b)]. Below the baryon-antibaryon threshold, this preferred breakup is not allowed; a major rearrangement (presumably at the cost of a considerable amount of energy) is then necessary for the diquark-antidiquark system to change itself into two separated ordinary mesons [Fig. 1(c)].

Another way to examine the rearrangement process is in terms of quark Harari-Rosner diagrams.[16] Figure 2(a) and 2(b) illustrate how a diquark-antidiquark system could decay into or-

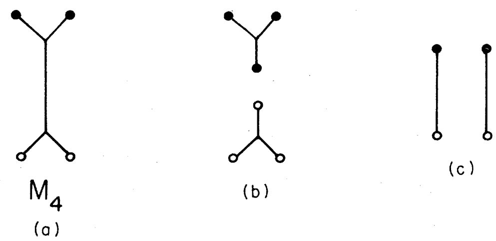


FIG. 1. (a) Diquark-antidiquark state M_4 in the string model, (b) its preferred decay to a baryon and antibaryon, (c) two ordinary mesons.

dinary mesons. However, both of these processes are disallowed by the generalized Okubo-Zweig-Iizuka (OZI) rule of Freund, Waltz, and Rosner,[17] whose two criteria (motivated by duality) for an allowed three-particle vertex are as follows:

(1) Quarks and antiquarks from the same particle cannot annihilate [this eliminates Fig. 2(a)];

(2) Any two of the three particles must share a quark line [this eliminates Fig. 2(b) since the two final-state mesons do not have any quark line in common].

Another approach which points to the weak coupling of baryonium states and ordinary mesons is the dual topological unitarization (DTU) scheme of Chew and collaborators.[18] There, an ordered baryonium state [Fig. 3(a)] cannot communicate with an ordered two-meson state [Fig. 3(b)] at the planar level; communication is achieved only through a higher-order process which corresponds in this scheme to a much weaker coupling.

As we see, none of the models gives, as yet, a compelling reason for the narrowness of these states, but collectively they give some indication that narrow states might exist. Even though one does not understand the cause of this narrowness, one can nevertheless ask the following important question: does the spectrum of states that are observed resemble in any way the spectrum of states which would be expected in a diquark-antidiquark excitation scheme? The present paper examines this question, and discusses one model in which the observed states do seem to have a rather natural assignment. We suggest several ways to test it experimentally.

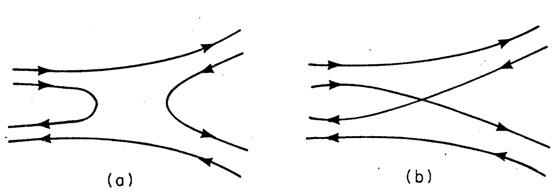


FIG. 2. Quark-line diagrams for a diquark-antidiquark state decay by (a) annihilation, (b) rearrangement. Both of these processes are forbidden by the generalized OZI rules of Ref. 17.

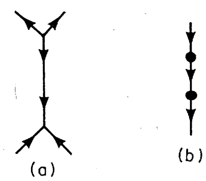


FIG. 3. (a) The baryonium state M_4, and (b) a two-meson state, in the DTU approach of Ref. 18.

Section II below reviews the properties of a diquark. The diquark-antidiquark spectrum (based on diquarks of color $\bar{3}_c$) is presented in Sec. III. This is followed in Sec. IV with a description of the model we suggest, and in Sec. V its spectrum involving only nonstrange quarks and antiquarks is compared with some of the observed states. An extension is made in Sec. VI to states containing one or more strange quarks. Section VII gives some brief comments on possible states of much higher mass but still narrow. We end (Sec. VIII) with a summary of our main ideas.

II. DIQUARKS

We start with a brief recapitulation of the properties of the diquark. Since each quark is a color-SU(3) triplet 3_c [we use the suffix c to distinguish the color-SU(3) representation from the flavor SU(3) and spin] and $3_c \otimes 3_c = \bar{3}_c \oplus 6_c$, a diquark can have color $\bar{3}_c$ or 6_c. The $\bar{3}_c$ combination is antisymmetric under the interchange of the two quarks, while the 6_c is symmetric. The color wave functions are to be combined with the flavor-spin SU(6) wave function such that the overall wave function of the diquark is antisymmetric. In SU(6), $\underline{6} \otimes \underline{6} = \underline{21} \oplus \underline{15}$ where $\underline{21}$ is the symmetric combination and $\underline{15}$ the antisymmetric one; their flavor-SU(3), spin-SU(2) content is

$$\underline{21} = \bar{3}^1 \oplus 6^3 , \quad \underline{15} = \bar{3}^3 \oplus 6^1 ,$$

where the superscripts 1, 3 are the SU(2) dimensionalities corresponding to a diquark of spin 0, 1, respectively. Thus by Fermi statistics, a diquark can either be of type $(\underline{21}, \bar{3}_c)$ or $(\underline{15}, 6_c)$. To form a physical (exotic) meson, a diquark should be taken with the corresponding antidiquark to obtain a color singlet.

Arguments exist, based on the saturation of interactions in a non-Abelian gauge theory, to indicate that the $\bar{3}_c$ diquark is bound, whereas the 6_c diquark is not.[19-21] One would expect therefore that the $\bar{3}_c \otimes 3_c$ states of a diquark and antidiquark should be lighter than the $6_c \otimes \bar{6}_c$ states, even if the latter exist at all. Furthermore, the $\bar{3}_c \otimes 3_c$ system can decay readily to a baryon-antibaryon pair (assuming we are above threshold) by the

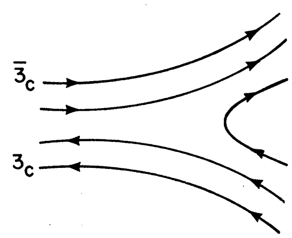


FIG. 4. Quark-line diagram for diquark-antidiquark decay into a baryon and antibaryon. This is allowed for color $\bar{3}_c$ diquarks, but not for color 6_c diquarks.

diagram of Fig. 4. The $6_c \otimes \bar{6}_c$ system cannot do this since $6_c \otimes 3_c$ and $\bar{6}_c \otimes \bar{3}_c$ do not contain color singlets. The $6_c \otimes \bar{6}_c$ mesons have been considered by Chan and Høgaasen[9] as an explanation of the narrow states above the $\bar{p}p$ threshold (to call such states baryonium is perhaps a misnomer since they have no reason for a strong coupling to the $\bar{p}p$ channel). We do not consider such $6_c \otimes \bar{6}_c$ states further in this paper apart from a brief mention in Sec. VII.

It is also possible to estimate the mass difference between a spin-triplet and spin-singlet diquark in a color $\bar{3}_c$. For example, it can be estimated from the mass difference between the $\Delta(1232)$ and the nucleon $N(938)$; the corresponding mass difference between spin-triplet and -singlet diquarks is given by $\frac{2}{3}(\Delta - N) \approx 200$ MeV. Rosenzweig[8] has suggested that a reasonable range for this mass difference is 200–300 MeV. (In the model we propose in Sec. IV, the value of 275 MeV is used, which is clearly consistent with these estimates from other sources.)

III. THE DIQUARK-ANTIQUARK SPECTRUM

We now develop the spectrum of states generated in a $21 \otimes \overline{21}$ diquark-antidiquark system. The set of states can be conveniently treated as of three types which arise from the flavor-spin combinations $\bar{3}^1 \otimes 3^1$, $(6^3 \otimes 3^1) \oplus (\bar{3}^1 \otimes \bar{6}^3)$, and $6^3 \otimes \bar{6}^3$. For convenience, we shall refer simply to these combinations as A, B, and C, respectively. It follows from the end of the previous section that one would expect the masses of the ground states of these three types to differ by 200–300 MeV as a spin-singlet diquark is replaced by a spin-triplet diquark.

The spins and parities of the various states generated in this scheme are shown in Table I, for orbital angular momentum $L = 0, 1, 2, 3$ between the diquark and antidiquark. The table can easily be extended to higher values of L. We do not consider systems in which the diquark itself is internally excited.

Clearly there is a vast multitude of states. One can never hope to see all of them, but fortunately certain reactions pick out particular sets of quantum numbers so that it still may be possible to see whether such an excitation scheme is a likely one. Electron-positron annihilations, for example, will automatically pick out $J^{PC} = 1^{--}$ states. Also, when

TABLE I. Spectrum of $\bar{3}_c \otimes 3_c$ diquark-antidiquark states. The quantum numbers $L, S, J, \cdots$ refer to the orbital angular momentum, the spin, the total angular momentum, $\cdots$ of the whole system.

	L	S	J	P	C_n	G $I=0$	G $I=1$
A: $\bar{3}^1 \otimes 3^1 = (1 \oplus 8)^1$	0	0	0	+	+	+	−
	1	0	1	−	−	−	+
	2	0	2	+	+	+	−
	3	0	3	−	−	−	+
B: $(6^3 \otimes 3^1) \oplus (\bar{3}^1 \otimes \bar{6}^3) = (8 \oplus 8 \oplus 10 \oplus \overline{10})^3$	0	1	1	+	±	±	∓
	1	1	2, 1, 0	−	±	±	∓
	2	1	3, 2, 1	+	±	±	∓
	3	1	4, 3, 2	−	±	±	∓
C: $6^3 \otimes \bar{6}^3 = (1 \oplus 8 \oplus 27)^{1 \oplus 3 \oplus 5}$	0	0	0	+	+	+	−
		1	1	+	−	−	+
		2	2	+	+	+	−
	1	0	1	−	−	−	+
		1	2, 1, 0	−	+	+	−
		2	3, 2, 1	−	−	−	+
	2	0	2	+	+	+	−
		1	3, 2, 1	+	−	−	+
		2	4, 3, 2, 1, 0	+	+	+	−
	3	0	3	−	−	−	+
		1	4, 3, 2	−	+	+	−
		2	5, 4, 3, 2, 1	−	−	−	+

antiprotons and protons annihilate at rest in their relative S state, emitting a photon, electric dipole transitions allow coupling to only the following limited kinds of states:

$$^3S_1(1^{--}) \to 2^{++}, 1^{++}, 0^{++}, \quad ^1S_0(0^{-+}) \to 1^{+-}$$

corresponding to the initial $\bar{p}p$ state in a spin triplet or singlet, respectively. Moreover, experiments studying $\bar{p}p \to \pi^+\pi^-$ pick out the (J^{PC}, I^G) combinations

$$l \text{ even: } J^{PC} = l^{++},\ I^G = 0^+,$$

$$l \text{ odd: } J^{PC} = l^{--},\ I^G = 1^+,$$

where l is the orbital angular momentum of the final two-pion system. If the final state is $\pi^0\pi^0$, there is the further restriction that l must be even.

IV. MASSES OF STATES WITH NONSTRANGE QUARKS

We shall consider first only those states with content $(qq, \overline{qq})$ where q and $\bar{q}$ are nonstrange quarks and antiquarks $u, d, \bar{u}, \bar{d}$. The general characteristics of these states are as follows: For states with masses below the $\bar{p}p$ threshold, their widths will be small, corresponding to the fact that they cannot decay into their preferred $\bar{p}p$ channel and are inhibited from rearranging into regular mesons. Above the $\bar{p}p$ threshold however, the $\bar{3}_c \otimes 3_c$ diquark-antidiquark system can easily couple to $\bar{p}p$, through the process shown in Fig. 4. States immediately above the $\bar{p}p$ threshold will still be fairly narrow due to lack of phase space, but above this transition region they will become much broader, unless for some reason they are unable to couple to the $\bar{p}p$ channel (for example they may have isospin $I = 2$).

With this restriction to states made up of nonstrange quarks, the A configuration contains only $I = 0$ combinations, the B configuration only $I = 1$, while the C configuration allows for $I = 0$, 1, and 2.

The model we propose is essentially contained in Fig. 5, to which we refer the reader. There the spectrum arising from the A, B, and C configurations is depicted. Successive levels correspond to orbital excitations $L = 0, 1, 2, \ldots$, and the states on the right indicate all the J^{PC} values allowed by spin and angular momentum couplings. In the B and C cases, each level indicated represents the average position of what will be a band of states, split by spin-orbit and spin-spin forces.

The spectrum is obtained in the following way. First, we allocate the states X reported by Pavlopoulos *et al.*[14] in $\bar{p}p \to X\gamma$ annihilation at rest. As we have remarked, these X states must have J^{PC}

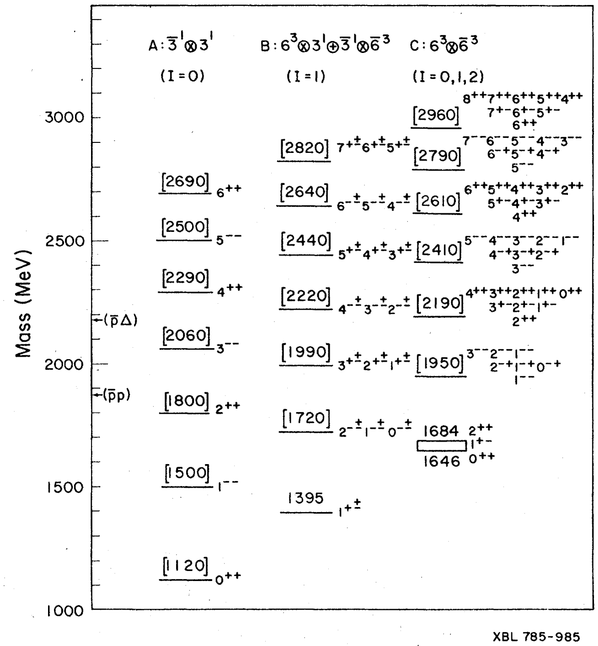


FIG. 5. Spectrum of states in the diquark-antidiquark scheme with nonstrange quarks and antiquarks. The three different types of configuration, A, B, C are indicated. Successive levels correspond to orbital angular momentum $L = 0, 1, 2, \cdots$ excitations. On the right hand side of each level on the various J^{PC} values which are allowed. The $\bar{p}p$ and $\bar{p}\Delta + p\bar{\Delta}$ thresholds occur at 1876 and 2170 MeV, respectively.

$= 0^{++}$, 1^{++}, 2^{++}, or 1^{+-}. These are precisely the quantum numbers of the diquark-antidiquark system with $L = 0$. It is natural then to assign the closely spaced 1684- and 1646-MeV states to the ground state of the C configuration. Three levels are expected there, while two lines have been distinguished experimentally. (Thus, either one level remains to be found in this mass region, or possibly one of the observed lines is in reality two lines very closely spaced.) Next, the third state at 1395 MeV is taken as belonging to the ground state of the B configuration: two levels are expected, one has been distinguished so far. Note that this allocation of the three X states is also reasonable from the point of view of mass differences. With these assignments, it would appear that the cost of replacing a $\bar{3}^1$ diquark with a 6^3 diquark is about $1670 - 1395 = 275$ MeV, taking the average mass of the C ground state to be about 1670 MeV. This falls within the 200–300-MeV range estimated for this mass difference (see the end of Sec. II).

The ground state of the A configuration is now predicted to be around 1120 MeV. (Predicted masses in Fig. 5 are shown in square brackets.) All the other levels follow with the further assumption that the excited state lies on straight-line Regge trajectories with typical slope $\alpha' \approx 1$ GeV^{-2}. They are given by the equations

$$m_A{}^2 = 1.25 + L\,,$$

$$m_B{}^2 = 1.95 + L\,,$$

$$m_C{}^2 = 2.79 + L\,,$$

where m is in GeV. A slope of 1 GeV^{-2} also corresponds to the slope of the leading trajectories in string models.[15]

V. DISCUSSION OF THE SPECTRUM WITH NONSTRANGE QUARKS

The model suggested above could of course be confirmed or rejected very easily if the J^{PC} of the X states seen in $\bar{p}p \to X\gamma$ were to be determined experimentally— do they have the quantum numbers as assigned? Such a determination seems difficult at present. What could be done however with improved resolution and statistics is to see whether any of the present lines are actually double lines, and to determine whether there are any lines in the vicinity of the ones already observed. (If, of course, for some reason annihilation in the spin-triplet $\bar{p}p$ state is preferred, the 1^{+-} lines will be diminished and no further lines should be seen.)

From Fig. 5, the model predicts the A-configuration ground state to be around 1120 MeV. This ground state has the right J^{PC} to be seen in the $\bar{p}p$ annihilation experiment, corresponding to a photon-emission line with energy 604 MeV. This is just beyond the range of the recent Pavlopoulos *et al.* experiment[14] (100–500 MeV), but clearly is worth hunting for. This may in fact be the best way of searching for the A-configuration ground level since, in pure hadronic channels, the 1.0–1.3-GeV mass region is well known to be fraught with problems. This is the region of the 0^{++} δ and ϵ mesons of the $^3P_0$ quark-antiquark system. To make matters even more complicated, another 0^{++} state in this region, at 1255 ± 5 MeV, with a width of 79 ± 10 MeV, has been reported by Cason *et al.*[22] Whether this is the A-configuration ground state, possibly broadened by mixing with nearby $q\bar{q}$ states, is not known. An extension of the photon-emission spectrum to higher energies would certainly be very helpful in resolving this situation.

If radial excitations are possible between the diquark and antidiquark, the 0^{++} A-configuration ground state will have a radial excitation at about 1500 MeV. (In Regge language, this is the daughter of the 1^{--} state at this mass value.) There would be a corresponding weak photon line at 338 MeV. However, we do not expect any other lines to be found in the photon spectrum above 100 MeV: the 2^{++} A state at 1800 MeV and the first radial excitation of the B ground stae would both yield very soft photons which would not be distinguishable from the large π^0-decay background.

Next, we discuss the $J^{PC} = 1^{--}$ states. From Fig. 5, we see that the number of 1^{--} states is surprisingly quite limited. The lowest one, which is predicted in our scheme, occurs in the $L = 1$ A configuration at 1500 MeV. This is precisely where a narrow peak (width $\lesssim 2.3 \pm 0.5$ MeV) is indeed observed at Adone,[13] an encouraging piece of agreement for the model. Since this state is composed solely of nonstrange quarks, we do not expect it to be associated with any excess of K mesons in its final decay products. (This contrasts with the first radial excitation of the ϕ meson which may be nearby; also this latter peak should be much broader.)

We note that the first radial excitation of this state is expected at about 1800 MeV, rather close to the observed peak[10–12] at 1812 MeV. However, as we shall discuss in the next section, another possible interpretation for the 1812-MeV peak is that it corresponds to a state containing strange quarks.

A 1^{--} state is also predicted in the B configuration occurring at about 1720 MeV. As far as we are aware, this region has not yet been scanned in detail either at Orsay or Adone. Further 1^{--} states with only nonstrange quarks are expected in the vicinity of 1950 and 2410 MeV from the C configuration. The former may well be the 1^{--} state reported some time ago at 1968 MeV in the reaction $\bar{p}p \to K^0_S K^0_L$ by Benvenuti *et al.*[23] The quoted width is 35 MeV, larger (as expected) than the narrow widths of the lower mass states because it lies above the $\bar{p}p$ threshold, but yet not too large because of the lack of phase space. The state which is predicted around 2410 MeV will be rather broad since there is no corresponding phase-space restriction, and may be rather difficult to observe.

Concerning the other states belonging to the $L = 1$ excitation of the B configuration around 1720 MeV, it is possible that one of them has been seen in the experiment of Gray *et al.*[24] who studied $\bar{p}d$ collisions at rest. They reported a state at 1794 MeV with a width of 15 ± 2 MeV; it had $I^G = 1^+$ and $J^P = 1^\pm$ or 2^-. If the spin-orbital splitting within our bands is the usual one with the largest spin lying highest, the most likely assignment in our model is the 2^- possibility. There is one puzzle, however, about this assignment. Gray *et al.* observed an enhancement in the four-pion and six-pion mass distributions (thus $G=+1$) but not in the distributions with an odd number of pions. Our model, on the other hand, would expect two approximately degenerate states with $G=\pm 1$. A more thorough study of this region is therefore highly desirable.

We now turn to levels lying above the $\bar{p}p$ threshold at 1876 MeV. Immediately above this threshold, states can still be narrow because of lack of phase space in the $\bar{p}p$ decay channel. This effect will be enhanced if the resonance has spin greater than 1, say; for example, 3^{--}, 2^{--}, and 2^{-+} states all require a D wave in the $\bar{p}p$ channel. As can be seen from Fig. 5, the band in our model closest to the $\bar{p}p$ threshold (the $L=1$ level in the C configuration) contains states with precisely these quantum numbers. Thus we would expect some evidence for narrow states around 1950 MeV. Again, there is a strong candidate for this band, in fact it is the best substantiated of all the heavier narrow states, called the S baryonium state.[25–28] It is seen in both total and elastic $\bar{p}p$ cross sections. Its mass is 1935 MeV and width $\lesssim 10$ MeV. It falls very naturally into our $L=1$ C band, and indeed Kalogeropoulos *et al.*[26] have suggested that it is a D-wave $\bar{p}p$ state. Moreover, it is possible that there is evidence for two states at this mass: the cross section for the charge-exchange process $\bar{p}p\to\bar{n}n$ does not show[29] any structure at 1935 MeV. The simplest explanation of this is to suppose destructive interference between two degenerate isospin 0, 1 resonances, though a fit to the data can be obtained without an extra resonance.[30]

Further above the $\bar{p}p$ threshold, states should become broader and broader since there is plenty of phase space for them to decay. Thus it is unlikely that many of the higher-lying states will be seen unless a very detailed study is made. This is what happens in the $\bar{p}p\to\pi^+\pi^-$ analysis of Carter *et al.*,[31] where both differential cross sections and polarizations have been measured over the laboratory momentum range 0.8 to 2.43 GeV/c. Because of the particles involved, only particular states are coupled such as (J^{PC}, I^G) corresponding to $(3^{--}, 1^+)$, $(4^{++}, 0^+)$, $(5^{--}, 1^+)$, $(6^{++}, 0^+)$, etc. In our model, where would we expect to see such states? From Fig. 5, we see that the $(3^{--}, 1^+)$ states first become important at around 1950 MeV; the $(4^{++}, 0^+)$ states at 2190–2290 MeV; the $(5^{--}, 1^+)$ states at around 2410 MeV; and the $(6^{++}, 0^+)$ states at 2610–2690 MeV. The masses of the first three of these states $(3^{--}, 4^{++}, 5^{--})$ obtained from the Carter *et al.* analysis[31] are 2150, 2310, and 2480, MeV respectively, with widths of 200 to 300 MeV. Thus the anticipated masses are all close to the observed masses at least to within their widths. (The anticipated mass of about 1950 MeV is perhaps a little low for the 3^{--} state, and may be due to the influence of the 3^{--} state in the nearby $L=3$ level of the B configuration at 2200 MeV.)

We note that there is other evidence[32–34] for these resonances, coming mainly from $\bar{p}N$ cross sections. The corresponding structures are usually referred to as the T and U regions. However, there are experiments[35,36] which do not see such structure. We refer the reader to the review of Eisenhandler[37] for a discussion of these results.

The clearest prediction for these high mass states is the $(6^{++}, 0^+)$ state which should be seen as a broad resonance in $p\bar{p}\to\pi^+\pi^-$ and $\pi^0\pi^0$ reactions around 2700 MeV. We recommend that experiments should be extended to examine this mass region. What are the chances of seeing the lower spin members in each band? Unfortunately it is a fact of life in phase-shift analyses of less-than-adequate data, that one is usually able to pick out only the contributing high angular momentum states. Other states that are approximately degenerate in mass as these, but which have smaller angular momentum, are much more difficult to discern. Thus, we do not expect many (if any) of the lower spin states in the various bands above the $\bar{p}p$ threshold to be seen.

There is, however, one other kind of state in the spectrum shown in Fig. 5 which would be worth searching for, namely the isospin $I=2$ states which are possible in the C configuration. These states do not couple to the $\bar{p}p$ channel which has $I=0, 1$ only. The important threshold for these $I=2$ states is the $(\bar{p}\Delta+p\bar{\Delta})$ threshold at 2170 MeV, though of course the Δ itself has a width so that the threshold is not a sharp one. This threshold lies close to our $L=2$ band in the C configuration, centered around 2190 MeV and which also contains states of appreciable angular momentum. It would appear therefore, if the model has any validity, that the best place to search for an $I=2$ exotic meson is in the mass region around 2190 MeV. This may well be the only place where one can detect such an object, since higher mass $I=2$ states will have very large widths (due to ample phase space in the $\bar{p}\Delta$ channel for decay, and the width of the Δ itself), thus making it extremely difficult for them to be seen.

There have been reports of several other heavy mass states,[38–41] but very narrow widths (less than 30 MeV) are quoted for them. These results need to be confirmed, but should they exist, they must be very unusual objects. They would not fit into the scheme discussed above, and we postpone discussion of them until Sec. VII.

VI. SPECTRUM OF STATES INCLUDING STRANGE QUARKS

Spectra similar to that shown in Fig. 5 may now be constructed by replacing the nonstrange quarks and antiquarks one at a time by strange quarks and antiquarks $s, \bar{s}$. For each replacement, there will be a mass increase corresponding to the mass difference between the strange and nonstrange quark. This mass difference can be estimated from the baryon octet, the baryon decuplet, and the vector meson nonet; yielding values in the range 130 to 190 MeV. For sake of discussion, we shall use the value of 160 MeV.

A general statement may be immediately made about these states with strange quarks and antiquarks—it is unlikely that many of them will be seen. The main reason for this is that the channels to which they like to couple are not easy to study experimentally. The candidates most likely to be detected are those near thresholds: for example, strangeness ±1 mesons (with quark content $qs\bar{q}\bar{q}$ or $qq\bar{s}\bar{q}$) of mass 2100 to 2300 MeV just above the $(\bar{p}\Lambda + p\bar{\Lambda})$ threshold; and strangeness ±2 mesons (with quark content $qq\bar{s}\bar{s}$ or $ss\bar{q}\bar{q}$) of mass 2300 to 2500 MeV near the $(\bar{p}\Xi + p\bar{\Xi})$ threshold. We do not discuss these states here, though they may be of great interest once good hyperon beam experiments become feasible.

Further, 1^{--} mesons, with quark content $qs\bar{s}\bar{q}$, appear in the scheme. They correspond to $L=1$ excitations in all A-, B-, and C-type configurations. They will be recognized from the 1^{--} mesons with quark content $qq\bar{q}\bar{q}$ by their higher probability of decaying and producing K mesons, arising from the $s, \bar{s}$ quarks. The lowest-lying state of this kind will occur at 1820 MeV in the A configuration. (Thus we have two reasons for a 1^{--} state to occur around this mass; as mentioned in the previous section, it lies close to the first radial excitation of the 1^{--} meson at 1500 MeV which contains only nonstrange quarks and antiquarks.) We note that a resonance near this mass has recently been reported at Adone.[13]

Several other closely spaced 1^{--} $qs\bar{s}\bar{q}$ states are expected just above 2 GeV. These come from the $L=1$ B configuration at 2040 MeV, the first radial excitation of the above 1820-MeV state from the $L=1$ A configuration at 2120 MeV, and the $L=1$ C configuration at 2270 MeV. Preliminary Adone results[13] indicate that there may be at least one resonance in this mass region; a substantial $K^*(890)$ signal is observed around 2130 MeV. While this is very encouraging, improved resolution and statistics will be necessary to study this region in detail to determine how many states are really present in this region.

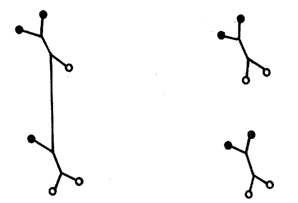
Finally, we comment on the most unusual combination of the form $ss\bar{s}\bar{s}$, which has $I=0$ and can arise only in the C-type configuration. A 1^{--} state is predicted at around 2590 MeV. If it is produced with a reasonable cross section, it should be easily recognizable by the copious K-meson production in its decay products. It is expected to be quite narrow since it lies very close to its associated baryon-antibaryon $\bar{\Xi}\,\Xi$ threshold at 2630 MeV.

Clearly, one could extend this scheme to consider the inclusion of charmed quarks and antiquarks. The lowest 1^{--} $qc\bar{c}\bar{q}$ states for example are expected to occur just above 4 GeV, a region which is known to contain a lot of structure. Some of these considerations have already been discussed by Rosenzweig[8] and we shall not pursue them here.

VII. NARROW STATES WELL ABOVE THE $\bar{p}p$ THRESHOLD

As we discussed, states which lie significantly above the $\bar{p}p$ threshold are expected in our model to be broad. A few high-mass narrow states however have been reported.[38–41] Their masses are 2020, 2200, 2600, 2850, 2950, and 3050 MeV, with widths in the range 20 to 40 MeV. These contrast with the other states observed in this mass region, such as the 3^{--}, 4^{++}, and 5^{--} states of Carter *et al.*,[31] whose widths were 200 to 300 MeV. The experimental evidence for these heavy narrow states is by no means convincing and it is very important to obtain their confirmation.

Should such heavy narrow states be found to really exist, they would not belong to the scheme we have described in the previous sections. (A fairly narrow state at 2020 MeV is just allowable in our model if it has spin 2 or 3, the spin factor suppressing the effect of increased phase space in the $\bar{p}p$ channel.) Chan and Høgaasen[9] have suggested that at least one of these states belong to a diquark-antidiquark scheme where the diquark has color 6_c. The coupling to the $\bar{p}p$ channel then remains weak since the process corresponding to that of Fig. 4 with the diquark-antidiquark in a $6_c \otimes \bar{6}_c$ does not occur. While this property provides an appealing explanation, there are, however, strong indications that 6_c diquarks are unlikely. In a simple color picture,[20,21] they are unbound (in contrast to the $\bar{3}_c$ diquark). Moreover, such 6_c systems do not exist in the usual string model; they require complicated combinations of strings, in contrast to the simple structure of Fig. 1(a) based on the $\bar{3}_c$ diquark. Likewise, in the dual topological unitarization scheme,[18] there is only one type of baryonium that appears, namely



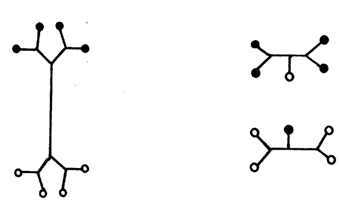
(a) M_6 (b) $M_4 + M_4$

FIG. 6. (a) String picture of a $(3q3\bar{q})$ system M_6, and (b) its preferred decay mode into two M_4 mesons.

that in Fig. 3(a), which is analogous to the color $\bar{3}_c$ diquark system in Fig. 1(a). Another indication of the unlikeliness of color 6_c diquarks is given in the recent work of Żenczykowski,[42] based on octonions[43]; this theory is related to string theories, and because of its special algebra, only color $\bar{3}_c$ exists.

It is perhaps too early to say much about high-mass narrow states since it may turn out that they do not exist. However, it is amusing to note an alternative to the 6_c diquark scheme, and that is the possibility that they correspond to even more complicated multiquark systems. The next two simplest types of multiquark systems consistent with the usual string model and lying on leading trajectories are shown in Figs. 6(a) and 7(a). Their preferred decays, obtained by cutting the central strings, are indicated in Figs. 6(b) and 7(b), respectively. Clearly, the sequence M_4, M_6, M_8, $\cdots$ may be continued.

It is even possible to make crude estimates of the masses of these objects by just adding quark masses together. We shall ignore spin effects and take the effective nonstrange quark mass from weighted spin average of the nucleon and Δ: its value is $\frac{1}{18}(4\Delta+2N)=380$ MeV. The masses of the objects M_4, M_6, and M_8 in Figs. 1(a), 6(a), and 7(a), respectively, are then estimated to be 1500 MeV (compared to 1535 MeV, the weighted spin average of our scheme in Fig. 5), 2250 MeV and 3000 MeV. The latter two objects have masses in the range of the reported peaks, and may be narrow for the same phase-space reasons that baryonium states (such as the 1935-MeV state) can be narrow. Similar estimates can be made for multiquark baryon-like objects. However, these calculations should not be taken seriously, but are merely to illustrate that, if high-mass narrow mesons are confirmed, multiquark configurations might be an interesting possibility to consider.



(a) M_8 (b) $B_5' + \bar{B}_5$

FIG. 7. (a) String picture of a $(4q4\bar{q})$ system M_8, and (b) its preferred decay mode.

VI. SUMMARY

We now summarize the main results of the model. The states of Pavlopoulos *et al.*, observed in $(\bar{p}p)\to X\gamma$ at 1684, 1646, and 1395 MeV, were used to pin down the $L=0$ levels of the B and C configurations of the diquark-antidiquark system. The spacings between successive orbital excitations were determined by assuming straight-line Regge trajectories of slope $\alpha'=1$. All other masses are then predicted. The other observed states were then accommodated (as described in more detail in the text) in the following way.

1500 MeV, 1^{--}, Ref. 13: This falls naturally into the $L=1$ level of the A configuration, predicted to be precisely at this mass.

1812 MeV, 1^{--}, Refs. 10–13: This lies in the region of the first radial excitation of the 1500-MeV state, and is the $qs\bar{s}\bar{q}$ partner of the 1500-MeV state.

1968 MeV, 1^{--}, Ref. 23: This is close to the $L=1$ level of the C configuration, predicted to occur around 1950 MeV.

2130 MeV, 1^{--}, Ref. 13: Several closely spaced states are expected around this mass, coming primarily from states with $qs\bar{s}\bar{q}$ content.

1794 MeV, Ref. 24: An $L=1$ state in the B configuration, 2^- favored.

1935 MeV, Refs. 25–28: This is expected to belong to the $L=1$ level in the C configuration, 2^- being favored. Both isospins $I=0, 1$ are possible.

2150 MeV, $(3^{--}, 1^+)$, Refs. 31–34: This is probably an $L=1$ state in the C configuration (expected at around 1950 MeV), with some admixture of $L=3$ from the B configuration (2220 MeV).

2310 MeV, $(4^{++}, 0^+)$, Refs. 31–34: This is a mixture of an $L=2$ C-configuration state (expected around 2190 MeV) and an $L=4$ A-configuration state (2290 MeV).

2480 MeV, $(5^{--}, 1^+)$, Ref. 31: This is most likely to be an $L=3$ C-configuration state (expected around 2410 MeV).

We have also speculated on more complicated multiquark systems as the origin of heavy-mass narrow states, should these be found to exist.

At the same time as being able to accommodate the above observed states, we have a large number of predictions and suggestions for future experimental study. Some of these are as follows, where estimated masses are indicated in square brackets.

States already seen in $(\bar{p}p) \to X\gamma$: Further lines are expected in the same vicinity, or possibly some of the lines already seen are double lines.

0^{++} [1120 MeV]: This is the ground state of the A configuration, and should be detectable from the photon spectrum in $\bar{p}p$ annihilations. (There may be complications due to mixing with other 0^{++} states in this region. It is possibly the 1255-MeV state reported in Ref. 22.)

0^{++} [1500 MeV]: This is the radial excitation of the A-configuration ground state. It should produce a weak photon line around 338 MeV in $(\bar{p}p)$ annihilations.

1^{--} [1720 MeV]: This arises in the $L=1$ level of the B configuration. It should be seen at Orsay and Adone in e^+e^- annihilations.

1^{--} [1950 MeV]: This state occurs in the $L=1$ level of the C configuration; it is possibly the 1968 MeV state of Ref. 23 mentioned above, and should also be seen in e^+e^- annihilations.

1^{--} [2590 MeV]: This also comes from the $L=1$ C level, but has the quark content $ss\bar{s}\bar{s}$. Copious K-meson production should accompany its formation in e^+e^- annihilations.

$(6^{++}, 0^+)$ [2700 MeV]: This comes from $L=4$ in the C configuration and $L=6$ in the A configuration which are closely spaced in mass. Higher-energy partial-wave analysis of $\bar{p}p \to \pi^+\pi^-$ and $\pi^0\pi^0$ should reveal this broad state.

$I=2$ [2190 MeV]: Isospin states with $I=2$ arise in the C configuration. The best chance of seeing such a state would be just above the $(\bar{p}\Delta + p\bar{\Delta})$ threshold, corresponding to $L=2$.

It will be a real test of the model if at least some of these states are observed.

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