Diquark model of exotic mesons

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Abstract. This is a conference mostly devoted to diquarks. Although an exotic meson can in principle be composed of a diquark and an antidiquark, such an exotic is unlikely to be experimentally observable in the near future. The reason, according to the model, is that diquark-antidiquark exotics have masses well above the threshold for decay into two mesons, and are likely to have widths too large to make them observable. A possible exception is a $u\bar{d}b\bar{b}$ exotic, but it will be a long time before such a state can be observed even if it is stable against strong decay.

\textsuperscript{1}Invited talk given by the first author at an international workshop, Diquarks 3, Torino, Italy, October 28–30, 1996. A shortened version will appear in the proceedings, to be published by World Scientific, Singapore.

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1. Introduction

An exotic meson has a structure which is different from that of a normal meson. This incomplete definition says what an exotic is not, but does not tell what it is.

A normal meson has the quantum numbers of a possible bound state of a quark and an antiquark: so-called normal quantum numbers. A meson which does not have normal quantum numbers is said to have exotic quantum numbers, and is by definition exotic. Some physicists think that mesons with exotic quantum numbers ought to exist because QCD does not obviously forbid them, but there is not yet definitive experimental evidence for the existence of any such meson.

A meson may have normal quantum numbers and still be exotic if its internal structure differs from that of a normal meson. Although there are candidates for such exotics, none has yet been positively identified. The problem of how to distinguish between a normal and an exotic meson with the same normal quantum numbers is a difficult one and remains unsolved, although progress has been made.

Even the structure of a normal meson is not simple, as the meson contains, in addition to a valence quark and antiquark, gluons and quark-antiquark pairs of the sea. It is convenient to simplify the problem by considering a model in which hadrons are made of constituent quarks, antiquarks, and gluons. A constituent quark is composed of a current quark plus a cloud of gluons and quark-antiquark pairs. The cloud has inertia, and so the mass of a constituent quark is larger than the mass of a current quark. Empirically, the mass difference between a constituent quark and a current quark of the same flavour is about 300 MeV. A constituent gluon is composed of a massless gluon surrounded by a cloud of gluons and pairs. Because a gluon has a stronger colour-charge than a quark, the inertia of its cloud is larger, and the mass of a constituent gluon is about 750 MeV.

In a model with only constituent quarks and constituent gluons, a normal meson is composed of a quark and antiquark. Among possible exotic mesons there might be glueballs (composed of gluons only), hybrids (composed of a quark, antiquark, and gluons), meson “molecules” (composed of two normal mesons), and diquark-antidiquark states. The evidence for the existence of exotic mesons is slowly accumulating, but is not yet definitive [1]. We use the notation “four-quark” state or “tetraquark” to refer to any exotic meson containing two quarks and two antiquarks, whether a diquark-antiquark state or a two-meson molecule.

An unambiguous signature for an exotic meson would be the discovery of a meson with quantum numbers which are impossible for a quark-antiquark pair. Among the possibilities are mesons with flavour quantum numbers greater than 1 or with two different flavours (not one flavour and another antiflavour) or mesons with combinations of spin, parity, and charge-conjugation parity which are forbidden to a quark-antiquark state. Unfortunately for the prospect of easy discovery of exotics, those with the lowest masses are likely to have normal quantum numbers, and furthermore, are likely to mix with ordinary quark-antiquark mesons.

2. Rough estimate of exotic meson masses

Let us crudely estimate the constituent mass of a light $u$ or $d$ quark and also the constituent mass of a gluon. We begin with the mass $m_q$ of a light $u$ or $d$ quark, neglecting their mass difference. One way we can estimate the mass is from the proton magnetic moment, assuming that the quarks have Dirac moments. This procedure gives

$$ m_q = m_p/\mu = 336 \text{ MeV}, $$

(2)

where $m_p$ is the proton mass and $\mu$ is the dimensionless ratio of the proton magnetic moment to one nuclear magneton. Another way to estimate $m_q$ is to take 1/2 the spin-averaged mass of the $\rho$ and $\pi$ mesons. (We are neglecting the meson binding energy in the absence of spin-dependent forces). This gives

$$ m_q = (3m_\rho + m_\pi)/8 = 306 \text{ MeV}. $$

(3)

Still a third way is to take 1/3 the appropriately spin-averaged mass of the nucleon and $\Delta$ [2], which gives

$$ m_q = (N + \Delta)/6 = 362 \text{ MeV}. $$

(4)

There is no fundamental reason for these methods to yield the same mass, but to a rough approximation they do. The average is 334 MeV; rounded to the nearest 10 MeV, it is

$$ m_q = 330 \text{ MeV}. $$

(5)
We interpret the constituent mass of a valence quark as its current mass plus the extra inertia of the sea of quark-antiquark pairs and gluons surrounding it. When the quark moves adiabatically, it drags this sea with it. (If we hit a quark violently, the sea does not follow along, and we measure the current mass.)

What is the extra inertia of the sea? We can safely neglect the current masses of the $u$ and $d$, which are just a few MeV. Therefore, we can interpret the quark constituent mass of about 330 MeV as in effect the mass of the part of the sea that is dragged along as the quark moves adiabatically.

We now make the conjecture that the mass of the relevant part of the sea is proportional to the square of the strong charge (or colour) of the quark. If so, the relevant quantity is the Casimir operator of SU(3), namely, $F^2$. This has the value $F^2_g = 4/3$ for a quark.

This little exercise enables us to estimate the mass of a constituent gluon (if, indeed, the concept of a constituent gluon makes sense). A gluon has a larger colour-charge than a quark; for a gluon, we have $F^2_g = 3$. Therefore, we find that the constituent gluon mass is

$$m_g = \left(\frac{F^2_g}{F^2_q}\right)m_q = \left(\frac{9}{4}\right)334 \text{ MeV} = 750 \text{ MeV},$$

again rounding to the nearest 10 MeV.

We are now able to obtain rough estimates of the masses of exotic mesons containing light quarks and/or glue. These estimates neglect hadron binding energies, and, in particular, neglect the effect of spin-dependent forces. Later we shall obtain estimates of some exotic masses in specific models.

We denote the mass of a meson by $M$, with subscripts denoting its constituents. A four-quark state has an estimated mass

$$M_{qqqq} = 4m_q = 1320 \text{ MeV},$$

a hybrid has an estimated mass

$$M_{qqg} = 2m_q + m_g = 1410 \text{ MeV},$$

and a glueball made of two constituent gluons has an estimated mass

$$M_{gg} = 2m_g = 1500 \text{ MeV}.$$

All these masses are in the same ballpark. Furthermore, excited quark-antiquark (two-quark) mesons also have masses in this region. Consequently, if quantum numbers permit, observed mesons with masses in the region, say, between 1300 and 1600 MeV are likely to be mixtures of two-quark, four-quark, hybrid, and glueball mesons. This mixing ought to occur even though most ground-state two-quark mesons are largely unmixed.

We can also estimate the masses of exotics containing other quark flavours. The mass differences between different flavoured quarks are roughly

$$m_s - m_q = 170 - 200 \text{ MeV},$$

$$m_c - m_s = 1160 - 1200 \text{ MeV},$$

$$m_b - m_c = 3340 - 3400 \text{ MeV}.$$ 

Therefore, replacing a light quark in an exotic by a heavier one will raise the mass of the exotic approximately by the appropriate quark mass difference. Actually, this approximation is likely to overestimate the mass of the heavier exotic because the binding energy, which we have neglected so far, increases with mass.

In order to go beyond rough estimates of exotic masses and to calculate exotic decay rates and branching fractions, we need to consider specific models. Some simple models can give precise predictions for masses and decay rates, but precision does not necessarily mean correctness. Most of us believe that QCD is the correct theory of strong interactions, but we do not know whether the predictions of simple models are anywhere near the predictions of QCD. Other models, such as lattice models of QCD are limited in precision by the numerical techniques used to evaluate them.

We concentrate on a model of exotic mesons composed of a diquark and an antidiquark. We shall discuss the strengths and weaknesses of the model, as well as giving its predictions about exotic mesons.
Work has been done with a number of other four-quark models, of which we mention the papers of Sylvestre-Brac and Semay [3] and Pepin et al. [4]. Other references are contained in these papers and in a review of diquarks [5].

3. A diquark model

In our scheme, an exotic hadron is composed of quark clusters [6], and we confine ourselves to the case in which the clusters are diquarks or antidiquarks. Now the $F_1 \cdot F_2$ factor in the lowest-order QCD potential between two quarks is positive for a sextet diquark but negative for a triplet (actually antitriplet) diquark, leading to a repulsive interaction between two quarks at small separations for the former and an attractive interaction for the latter. Therefore, we expect that colour-sextet diquarks will lie higher in energy than the colour-triplet diquarks. While we neglect the former, on general grounds we expect that their effect could slightly lower the ground state energy compared to our finding. We do not, however, have a simple recipe to propose in order to give a quantitative estimate of this effect.

We now consider a detailed model which allows us to obtain the masses of exotic mesons in terms of the masses of mesons and baryons. Many of the meson and baryon masses are known either from experiment or from predictions for unknown hadrons based on the systematics of known hadrons [7,8]. We can use this information as input data to obtain specific predictions for the masses of exotics. Our model has the advantage that we do not need to assume an explicit Hamiltonian to describe the interaction, but there is the accompanying disadvantage that the model does not allow us to calculate decay rates. We can, however, make some qualitative remarks about decays.

According to QCD, in first approximation, the force between two coloured particles depends only on their colour configuration and not on their mass or spin. This fact gives rise to an approximate supersymmetry between a diquark and antiquark. A discussion of this supersymmetry, with references, is contained in the diquark review [5].

We neglect spin at the outset of our treatment, but subsequently take it into account. However, we cannot neglect the effect of mass because, even if the force does not depend on the constituent masses, the meson mass does. The mass of a composite particle is the sum of the masses of the constituents plus an interaction energy. In general, this interaction energy also depends on the constituent masses even if the force does not.

In our approximation, the force between a quark and an antiquark in an overall colour-singlet state is the same as the force between an antidiquark and a diquark in an overall colour singlet. Consequently, we can equate the mass of an exotic meson composed of a diquark and antidiquark to the mass of a meson composed of a fictitious quark and antiquark having the same masses as the diquarks and antidiquarks.

Two obstacles must be overcome in order to carry out this procedure: we must obtain estimates of the masses of diquarks, and we must obtain the interaction energy of two fictitious quarks having the same masses as the diquarks.

Let us first consider the problem of obtaining the interaction energy of a bound quark and antiquark with any masses. The interaction energy turns out to be a fairly smooth function of the reduced mass of the two particles [7]. We assign reasonable values of the masses to the different flavoured quarks. To be specific, we use the same quark masses as in ref. [8], which are (in MeV):

$$m_q = 300, \quad m_s = 475, \quad m_c = 1640, \quad m_b = 4985.$$  \hspace{1cm} (13)

These masses are a little below those given in our rough estimates in Eqs. (5) and (10)–(12). This is not important, as we have found [7,8] that we may vary the input quark masses appreciably without significantly changing the output hadron masses, as we can make compensating changes in the interaction energy. Our approach [7,8] is much more sensitive to the differences of quark input masses than to their absolute values.

If we use the experimental values $M_{12}$ of meson masses [1] as input, we can calculate the interaction energies $E_{12}$ from the simple formula:

$$E_{12} = M_{12} - m_1 - m_2.$$  \hspace{1cm} (14)

In order to eliminate the effects of spin as much as possible in this procedure, we use spin-averaged meson and baryon masses according to the prescription of Ref. [2]. This procedure cannot always be carried out
in terms of known hadron masses. Where necessary, we approximately remove the effect of the colour-
magnetic interaction by a semi-empirical mass formula \[9\].

We can then plot the values of \(E_{12}\) against the reduced mass \(\mu_{12}\). We obtain the value of \(E_{12}\) for any \(\mu_{12}\) by interpolation or extrapolation, or, in other words, from the mass given by a smooth curve
connecting the known points. Thus, if we are given the masses of any two diquarks, we compute the
reduced mass, find the relevant interaction energy from the curve for mesons, add the two diquark masses,
and thereby obtain the mass of the exotic composed of the two diquarks.

We next turn to the problem of estimating the diquark masses. Consider the spin average of the masses
of ground-state baryons with a given quark content. The individual baryon masses are known either from
experiment \[1\] or from estimates based on the systematics of known baryons \[7,8\]. For a baryon like the
\(\Omega\), which contains the quarks \(sss\), spin averaging in terms of known baryons cannot be done. In such cases
we use the semi-empirical formula \[9\].

We assume the baryon is composed of a diquark and a quark. If the quarks have different flavours,
then we assume that the two heaviest quarks form the diquark. (We neglect the mass difference between
the \(d\) and \(u\) quarks.) We then guess a trial value for the diquark mass; it is convenient to take the sum of
the masses of the two quarks in the diquark. We then find the reduced mass of the diquark and the third
(or spectator) quark, use the meson curve to obtain the interaction energy, and so obtain a prediction for
the baryon mass, which, in general, will not be the same as the input baryon mass. However, we can then
use a revised diquark mass and repeat the process by iteration, stopping when we have found an input
diquark mass that gives the input value of the baryon mass. The difference in mass between a diquark and
the sum of the masses of the quarks it contains is the triplet interaction energy \(E_{12}^t\). We expect that the
energy \(E_{12}^t\) is larger than \(E_{12}\) because the interaction at small distances contains the factor \(F_1 \cdot F_2\), which
is smaller in magnitude for two quarks in a colour-triplet (actually, antitriplet) state than in a colour-singlet
state. We find numerically that our expectation is satisfied.

We must overcome still another difficulty. If we use the above iteration procedure to calculate the
mass of, say, the \(ss\) diquark, the result depends mildly on whether the spectator quark in the baryon is \(q\)
\((u\) or \(d\)) or \(s\). We resolve the ambiguity by averaging the two values.

The above procedure gives us diquark masses that are suitable for use in calculating the masses of
exotic mesons except that so far we have not included the effects of spin. We therefore have to correct
the diquark masses for spin-dependent forces. We do so under the assumption that these forces arise from
the colour-magnetic interaction of perturbative QCD or from a generalization of this interaction \[2, 7, 8\].
Then, any pair of quarks in a baryon is subject to essentially the same spin-dependent force as the same
two quarks in an exotic meson, provided the two quarks belong to a single diquark.

The magnitude of the colour-magnetic energy arising from two quarks in a baryon has already been
estimated \[2, 7, 8\] and found to be only weakly dependent on the mass of the spectator quark. This
dependence is such that the magnitude of the colour-magnetic energy increases slightly as the mass of the
third quark increases. We approximate the colour-magnetic energy by taking an average of the energy
obtained with the \(q, s,\) and \(c\) as spectator. (We do not include the \(b\) as spectator because the result is very
similar to the \(c\) with a larger error and because we do not want to give too much importance to the heavy
quarks.) A different prescription will change our results by only a few MeV at most. We can now obtain
all the necessary colour-magnetic energies from the results in Refs. \[2, 7, 8\].

The above procedure lets us correct the masses of the diquarks for the effects of spin. However, in
general, in an exotic meson there are still other spin-dependent forces arising between the quarks in the
diquark and the quarks in the antidiquark. However, if either the diquark or antidiqurk has spin zero, the
net effects of these spin-dependent inter-diquark forces vanish. Although we have a method that applies to
exotics containing two spin-one diquarks, here we restrict ourselves for simplicity to exotics with at least
one diquark of spin zero. These latter exotics have the lowest masses in any case.

4. Results and discussion

As we stated in the previous section, we obtain diquark masses in terms of input baryon masses
and estimates of the colour-magnetic interaction energies between pairs of quarks in baryons. Strictly
speaking, the calculated diquark masses depend slightly on the mass of the spectator quark in the baryon.
The differences, however, are usually less than 20 MeV. In those cases in which we obtain more than one
value of the diquark mass, we give the average value. These average values of the diquark masses are shown in Table 1.

Table 1. Masses $M_0$ and $M_1$ of spin-zero and spin-one diquarks obtained from input baryon masses and colour-magnetic interaction energies in baryons. The method is described in more detail in Sec. 3. The symbol $q$ stands for $u$ or $d$, and masses are rounded to the nearest 5 MeV. Errors of up to 20 MeV arise because, in our model, the calculated diquark masses depend on the spectator quark, and we have averaged over this dependence.

| Quark content | $M_0$ (MeV) | $M_1$ (MeV) |
|---------------|-------------|-------------|
| $qq$          | 595         | 800         |
| $qs$          | 835         | 975         |
| $ss$          | -           | 1150        |
| $gc$          | 2100        | 2150        |
| $sc$          | 2250        | 2295        |
| $cc$          | -           | 3415        |
| $gb$          | 5465        | 5485        |
| $sb$          | 5630        | 5650        |
| $cb$          | 6735        | 6750        |
| $bb$          | -           | 10075       |

Using the diquark masses in Table 1, we can compute the reduced mass of a system of a diquark and antidiquark. We then obtain the interaction energy for the reduced mass, using the meson curve as input. This procedure gives us the exotic meson mass. We have already taken into account the colour-magnetic interaction in computing the diquark masses. Because we restrict ourselves to those cases in which at least one diquark has spin zero, no further spin-dependent forces enter the problem. The calculated exotic masses are shown in Table 2. We also give in Table 2 the lightest mesons into which the exotic can decay strongly, provided the energy permits. The sum of the masses of the decay products are shown in the last column of Table 2.

The calculated exotic masses given in Table 2 have errors of up to 30 MeV associated with the fact that we have chosen the fixed diquark masses of Table 1, whereas actually, in our model, the diquark masses depend on their environment. If future experiments should yield masses which differ from those in Table 2 by much more than 30 MeV, we will have to discard our model in its present form.

We see from Table 2 that only the exotic $qq\bar{b}\bar{b}$ lies below the threshold of the lightest mesons into which it can decay strongly. The exotic $qs\bar{b}\bar{b}$ lies only a little above threshold. It may be observable as a narrow resonance or even a bound state, as our model is probably not accurate enough to distinguish these possibilities in this case. However, exotic mesons with two $b$ quarks are unlikely to be seen for quite some time.

The exotic masses we have calculated depend on the input masses of mesons and baryons. Because some of these input masses are not known from experiment but are estimated, we have an additional source of error. In particular, the estimation of the masses of baryons containing two heavy quarks involves a considerable extrapolation from known data [8]. This fact adds to the uncertainty in our calculated masses of exotics containing two heavy quarks.

All exotics with at most one heavy quark have masses well above the masses of the decay products, as we see from Table 2. This means that these exotics will decay rapidly into two mesons. Our method does not allow us to calculate the decay widths (because we do not have a Hamiltonian or spatial wave functions). However, we observe that the colour wave functions of the exotics are not orthogonal to the colour wave functions of the two mesons into which they can decay. This means that there is nothing to prevent the exotics from “falling apart” into their decay products. Under these circumstances, we guess that the exotics will have widths too large to make these mesons observable.
It is possible that the spin-dependent forces arise, not from the colour-magnetic interaction but from pseudoscalar meson exchange [10, 11]. If so, some exotic mesons with two \( c \) quarks are predicted [4] to have masses well below those given in our Table 2 and to be stable against strong decay. Future experiments, by their observation or non-observation of weakly decaying exotics containing two \( c \) quarks, will rule out either our model or the one of Ref. [4].

We should like to thank Ted Barnes, Michael Pennington, and Jean-Marc Richard for valuable discussions. This work was supported in part by the U.S. Department of Energy, the U.S. National Science Foundation, by the Italian Institute for Nuclear Physics (INFN) and by the Ministry of Universities, Research, Science and Technology (MURST) of Italy.

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Table 2. Predicted masses $M_E$ of exotic mesons obtained from the diquark masses in Table 1 by the method described in Sec. 3. These are all ground-state mesons with the given spin and quark content, and the parities are all positive. The symbol $q$ stands for $u$ or $d$, and masses are rounded to the nearest 10 MeV. The two numbers in column 2 are the spin of the diquark and antidiquark respectively; the spin of the exotic is just the sum of these spins. The next-to-last column gives the lowest-mass mesons into which the exotic can decay strongly if energetically permitted, and the last column gives the threshold energy $E_t$ of the decay. Errors of up to 30 MeV in the exotic masses arise because of errors in the diquark masses.

| Quark content | Diquark spins | $M_E$ (MeV) | Decay products | $E_t$ (MeV) |
|---------------|---------------|-------------|----------------|------------|
| $qqq\bar{q}$  | 0, 0          | 1180        | $\pi\pi$       | 280        |
| $qqq\bar{q}$  | 0, 1          | 1370        | $\pi\rho$      | 910        |
| $qqqs$        | 0, 0          | 1400        | $\pi K$        | 630        |
| $qqqs$        | 0, 1          | 1530        | $\pi K^*$      | 1030       |
| $qqqs$        | 1, 0          | 1580        | $\pi K^*$      | 1030       |
| $qqs\bar{s}$  | 0, 1          | 1700        | $KK^*$         | 1390       |
| $qqs\bar{s}$  | 0, 0          | 1610        | $KK$           | 990        |
| $qqs\bar{s}$  | 0, 1          | 1740        | $K^*K, K\bar{K}^*$ | 1390 |
| $qgqc$        | 0, 0          | 2620        | $\pi\bar{D}$   | 2010       |
| $qgqc$        | 0, 1          | 2660        | $\pi\bar{D}^*$ | 2150       |
| $qgqc$        | 1, 0          | 2770        | $\pi\bar{D}^*$ | 2150       |
| $qgq\bar{b}$  | 0, 0          | 5950        | $\pi B$        | 5420       |
| $qgq\bar{b}$  | 0, 1          | 5970        | $\pi B^*$      | 5460       |
| $qgq\bar{b}$  | 1, 0          | 6100        | $\pi B^*$      | 5460       |
| $qgq\bar{b}$  | 0, 1          | 1900        | $K\phi$        | 1520       |
| $qgq\bar{b}$  | 0, 1          | 1740        | $K^*K, K\bar{K}^*$ | 1390 |
| $qgq\bar{b}$  | 1, 0          | 2920        | $K\phi$        | 1520       |
| $qgq\bar{b}$  | 0, 1          | 1900        | $K^*\eta$      | 1440       |
| $qgq\bar{b}$  | 0, 1          | 2760        | $K\bar{D}$     | 2360       |
| $qgq\bar{b}$  | 0, 1          | 2810        | $K\bar{D}^*$   | 2500       |
| $qgq\bar{b}$  | 1, 0          | 2920        | $K\bar{D}^*$   | 2500       |
| $qgq\bar{b}$  | 0, 1          | 2880        | $\pi D_s$      | 2110       |
| $qgq\bar{b}$  | 0, 1          | 2850        | $\pi D_s^*$    | 2250       |
| $qgq\bar{b}$  | 0, 1          | 2920        | $\pi D_s^*$    | 2250       |
| $qgq\bar{b}$  | 0, 1          | 2950        | $K D_s$        | 2360       |
| $qgq\bar{b}$  | 0, 1          | 2990        | $K D_s^*$      | 2610       |
| $qgq\bar{b}$  | 1, 0          | 3060        | $K D_s^*$      | 2610       |
| $qgq\bar{b}$  | 0, 1          | 3060        | $K D_s^*$      | 2610       |
| $qgq\bar{b}$  | 0, 1          | 3210        | $\phi D_s$     | 2990       |
| $qgq\bar{b}$  | 1, 0          | 3210        | $\phi D_s^*$   | 2660       |
| $qgq\bar{b}$  | 0, 0          | 6120        | $KB$           | 5780       |
| $qgq\bar{b}$  | 0, 1          | 6140        | $KB^*$         | 5910       |
| $qgq\bar{b}$  | 1, 0          | 6260        | $KB^*$         | 5910       |
| $qgq\bar{b}$  | 0, 1          | 6120        | $\pi B_s$      | 5510       |
| $qgq\bar{b}$  | 0, 1          | 6140        | $\pi B_s^*$    | 5550       |
| $qgq\bar{b}$  | 1, 0          | 6230        | $\pi B_s^*$    | 5550       |
| $qgq\bar{b}$  | 0, 0          | 6280        | $KB_s$         | 5860       |
| $qgq\bar{b}$  | 0, 0          | 6280        | $KB_s^*$       | 5860       |
| $qgq\bar{b}$  | 0, 1          | 6300        | $KB_s^*$       | 5830       |
| $qgq\bar{b}$  | 0, 1          | 6390        | $KB_s^*$       | 5830       |
Table 2 continued.

| Quark content | Diquark spins | $M_E$ (MeV) | Decay products | $E_t$ (MeV) |
|---------------|---------------|-------------|----------------|-------------|
| $qs\bar{s}\bar{s}$ | 0, 1 | 6360 | $KB_s^*$ | 5910 |
| $ss\bar{b}\bar{b}$ | 1, 0 | 6530 | $\phi B_s$ | 6390 |
| $qq\bar{c}\bar{c}$ | 0, 1 | 3910 | $DD^*$ | 3880 |
| $qc\bar{q}\bar{c}$ | 0, 0 | 3920 | $\pi \eta_c$ | 3120 |
| $qc\bar{q}\bar{c}$ | 0, 1 | 3970 | $\pi J/\psi$ | 3240 |
| $qs\bar{c}\bar{c}$ | 0, 1 | 4090 | $D\bar{D}_s^*$ | 4010 |
| $qc\bar{c}\bar{c}$ | 0, 0 | 4060 | $K\eta_c$ | 3470 |
| $qc\bar{c}\bar{c}$ | 0, 1 | 4110 | $KJ/\psi$ | 3590 |
| $qc\bar{c}\bar{c}$ | 1, 0 | 4110 | $KJ/\psi$ | 3590 |
| $sc\bar{s}\bar{c}$ | 0, 1 | 4200 | $D_s\bar{D}_s$ | 3940 |
| $sc\bar{s}\bar{c}$ | 0, 1 | 4240 | $D_s\bar{D}_s^*, D_s^*\bar{D}_s$ | 4080 |
| $qq\bar{c}\bar{b}$ | 0, 0 | 7220 | $D\bar{B}$ | 7150 |
| $qq\bar{c}\bar{b}$ | 0, 1 | 7230 | $D\bar{B}_c^*$ | 7190 |
| $qq\bar{c}\bar{b}$ | 1, 0 | 7360 | $D\bar{B}_c^*$ | 7190 |
| $qc\bar{q}\bar{b}$ | 0, 0 | 7180 | $\pi \bar{B}_c$ | 6390 |
| $qc\bar{q}\bar{b}$ | 0, 1 | 7200 | $\pi \bar{B}_c^*$ | 6460 |
| $qc\bar{q}\bar{b}$ | 1, 0 | 7220 | $\pi \bar{B}_c^*$ | 6460 |
| $qs\bar{c}\bar{b}$ | 0, 0 | 7380 | $D\bar{B}_s$ | 7240 |
| $qs\bar{c}\bar{b}$ | 0, 1 | 7400 | $D\bar{B}_s^*$ | 7280 |
| $qs\bar{c}\bar{b}$ | 1, 0 | 7490 | $D\bar{B}_s^*$ | 7280 |
| $qc\bar{s}\bar{b}$ | 0, 0 | 7340 | $K\bar{B}_c$ | 6750 |
| $qc\bar{s}\bar{b}$ | 0, 1 | 7360 | $K\bar{B}_c^*$ | 6820 |
| $qc\bar{s}\bar{b}$ | 1, 0 | 7380 | $K\bar{B}_c^*$ | 6820 |
| $qb\bar{s}\bar{c}$ | 0, 0 | 7310 | $K\bar{B}_c$ | 6750 |
| $qb\bar{s}\bar{c}$ | 0, 1 | 7350 | $K\bar{B}_c^*$ | 6820 |
| $qb\bar{s}\bar{c}$ | 1, 0 | 7330 | $K\bar{B}_c^*$ | 6820 |
| $qs\bar{s}\bar{c}$ | 1, 0 | 7620 | $\bar{D}_s\bar{B}_s^*$ | 7380 |
| $sc\bar{s}\bar{b}$ | 0, 0 | 7470 | $\bar{B}_s\bar{D}_s$ | 7300 |
| $sc\bar{s}\bar{b}$ | 0, 1 | 7490 | $\bar{B}_s^*\bar{D}_s$ | 7340 |
| $sc\bar{s}\bar{b}$ | 1, 0 | 7520 | $\bar{B}_s^*\bar{D}_s$ | 7340 |
| $sc\bar{s}\bar{b}$ | 1, 0 | 7520 | $\bar{B}_s^*\bar{D}_s$ | 7340 |
| $qq\bar{b}\bar{b}$ | 0, 1 | 10550 | $\bar{B}_s^*\bar{D}_s$ | 10600 |
| $qb\bar{b}\bar{b}$ | 0, 1 | 10380 | $\pi \eta_b$ | 9540 |
| $qb\bar{b}\bar{b}$ | 0, 1 | 10800 | $\pi \Upsilon$ | 9600 |
| $qs\bar{b}\bar{b}$ | 0, 1 | 10710 | $BB_s^*$ | 10700 |
| $qb\bar{s}\bar{b}$ | 0, 0 | 10550 | $K\eta_b$ | 9900 |
| $qb\bar{s}\bar{b}$ | 0, 1 | 10570 | $K\Upsilon$ | 9960 |
| $qs\bar{s}\bar{b}$ | 0, 0 | 10710 | $B_s\bar{B}_s$ | 10470 |
| $qs\bar{s}\bar{b}$ | 0, 1 | 10730 | $B_s^*\bar{B}_s$ | 10780 |
| $qs\bar{s}\bar{b}$ | 0, 1 | 10730 | $\eta \Upsilon$ | 9950 |