Isovector and hidden-beauty partners of the $X(3872)$

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The isovector partners of the $X(3872)$, recently found at BES III, Belle and CLEO-c were predicted in a simple model based on the chromomagnetic interaction among quarks. The extension to the hidden-beauty sector is discussed.

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1. Introduction

Recently, a new hidden-charm meson was seen at BES III and Belle [1,2]. Its remarkable feature, as compared to most previous $X$, $Y$, $Z$ states is that it carries an electric charge. It is currently named $X(3900)^+$. Shortly after its announcement, its existence was confirmed by the Northwestern group working on CLEO-c data [3], who also have some indication for the neutral partner of the isospin triplet.

Note that three other charged states with hidden charm have been observed, $Z(4050)^+$, $Z(4250)^+$ and $Z(4450)^+$, but only by the Belle Collaboration. The $Z(4050)^+$ and $Z(4250)^+$ were seen by Belle in the $B$ decay [4], but not confirmed in a search by Babar [5]. The $Z(4450)^+$ was seen by Belle in the $\pi^0\psi'$ invariant mass of the $B \to K\pi^0\psi'$ decay [6,7], and the quantum numbers $I^G$ are favoured [8]. To our knowledge, this state was not confirmed in other channels or other experiments.

Two charged states have been seen in the hidden-beauty sector, the $Z_b(10610)^+$ and the $Z_b(10650)^+$, again by the Belle Collaboration [9]. The latest result deals with the $Z_b(10610)^0$ discovered by Belle [10], the neutral partner of the $Z_b(10610)^\pm$.

The $X(3872)$ has $J^{PC}=1^{++}$ as early indicated in several experiments (see, e.g., [11]), and confirmed recently at the Large Hadron Collider of CERN (LHC) (see, e.g., the analysis by LHCb [12]). The simplest scenario is that the new $X(3900)^+$ has the same $J^P$ quantum numbers as the $X(3872)$, namely $J^P=1^+$. A major issue is whether the $X$, $Y$ and $Z$ states are mostly molecules, i.e., bound states or resonances made of a flavoured meson and an anti-flavoured meson, or mostly a tetraquark states in which the quark interact directly. An analysis of the production rate of $X(3872)$ in [13,14] indicates that the measured cross section at Tevatron is too large for a molecule interpretation, even after taking into account the re-scattering effect suggested in [15].

The problem is to find a simple explanation for the approximate degeneracy of the isospin $I=0$ and $I=1$ states. In the molecular model, the $X(3872)$ is mainly a $\bar{D}D^*$ + c.c. state, and an important contribution to binding comes from the one-pion exchange, which includes an isospin-dependent factor $\tau_1 \tau_2$ whose absolute value is weaker for $I=1$ than $I=0$. In short, the molecular model of $X$, $Y$, $Z$ states favours isospin $I=0$ states, as did earlier the nucleon–antineutron model of the baryonium resonances [16].

On the other hand, the quark model with a flavour-independent interaction gives a natural explanation to “exchange-degeneracy”, with, e.g., $\omega$ and $\rho$ exactly degenerate as long as the quark–antiquark internal annihilation and the coupling to decay channels...
are neglected. Thus if the $X(3872)$ and the $X(3900)^+$ have the same $J^P$, it is tempting to seek an explanation in terms of quark dynamics, rather than in a molecular picture. Indeed, some models based on quark dynamics have predicted the isospin $I = 1$ state $X(3900)^+$ near its $I = 0$ partner $X(3872)$. This is the case for the chromomorphic model discussed below and for the diquark model of Ref. [17].

This property of exchange degeneracy illustrates the similarities and differences between QED and QCD. After the work of De Rújula, Georgi and Glashow [18], it has become widely accepted that the pattern of spin–spin splittings in quark models is similar in structure to that of the hyperfine splittings in atomic physics, namely is due to an interaction among chromomagnetic moments. In the case of the positronium atom, the interaction between the magnetic moments explains only about half of the energy difference between the spin-triplet and the spin-singlet states. The hyperfine splitting in positronium receives a substantial contribution from the annihilation diagram where the electron–positron pair are mostly in a colour-octet state. Should the Pauli principle can induce some effect, as the gluon transforms as an octet in colour. But the gluon transforms as a colour-octet state.

The difficulty in our model (1) consists in identifying a situation which reads

$$
\delta H = \begin{pmatrix} 2m_u - a & -a & -a \\ -a & 2m_d - a & -a \\ -a & -a & 2m_s - a \end{pmatrix}.
$$

We now have to fix the value of the parameter $a$ governing the annihilation term. In the baryonium atom, the virtual process $e^+ + e^- \rightarrow \gamma \rightarrow e^+ + e^-$ contributes to the hyperfine splitting, in addition to the Breit–Fermi interaction. The effect is given by the Pirenne potential [20]. Its strength is three times that of the Breit–Fermi contact interaction. The analogue for QCD has been discussed in the context of states on baryonium and other exotic states [21–23]. In the perturbative limit, there is an additional factor 2 due to colour, besides the factor 3 in QED. However, as stressed by Gelmini, the annihilation is substantially suppressed by the confinement of the gluons. So, instead of $a = 6C_\text{QCD}$, a choice $a \sim C_\text{QCD}$ is reasonable.

In [19], the values $a = 15$ MeV and $m_u - m_d = 3.5$ MeV were adopted, leading to a difference of about 31 MeV between the two eigenvalues, leading the prediction of about 3904 MeV for the neutral $I = 1$ partner of the $X(3872)$.

For the charged states of the $I = 1$ multiplet, $\delta H$ is simply replaced by $m_u + m_s$, and this puts the charged states about 0.4 MeV below the neutral, mostly isovector, one.

3. Extension to the hidden-beauty sector

The difficulty in our model (1) consists in identifying a single effective mass for a flavoured quark in open-flavour mesons, flavoured baryons and hidden-flavour mesons. The combinations

$$3(Q \bar{Q})_{S=1} + (Q \bar{Q})_{S=0} = 4m_Q + 4m_{\bar{Q}},
$$

$$2\Sigma_Q^+ + \Sigma_Q + \Lambda_Q = 4m_Q + 8m_{\bar{Q}},$$

$$3(Q \bar{Q})_{S=1} + (Q \bar{Q})_{S=0} = 8m_Q,
$$

should be compatible, and in particular, one should verify

$$\delta M = 12(Q \bar{Q})_{S=1} + 4(Q \bar{Q})_{S=0} - 4\Sigma_Q^+ - 2\Sigma_Q - 2\Lambda_Q
$$

$$- 3(Q \bar{Q})_{S=1} - (Q \bar{Q})_{S=0} = 0.$$  

In the charm sector, one gets $\delta M \approx -200$ MeV, which is rather satisfactory, but for the beauty sector, the result is $\delta M \simeq 1000$ MeV. It indicates that the bottomonium states give an average quark mass $m_b = 4721$ MeV, much lighter than the combination $m_b = (1227 + 4B + 4\Sigma_b - 2\Sigma_b - 2\Lambda_b)/8 = 4852$ MeV deduced from heavy-light systems. This is due to the strong chromoelectric attraction between two heavy quarks in $(bb)$.

We thus generalize our model to include a chromoelectric term, and replace (1) by

$$H = M + M_{\text{CE}} + H_{\text{CM}}
$$

$$= \sum_i m_i - \sum_{i,j} A_{ij} \lambda_i \bar{\lambda}_j - \sum_{i,j} C_{ij} \lambda_i \bar{\lambda}_j \sigma_i \sigma_j.
$$

Introducing a few non-vanishing chromo-electric coefficients $A_{ij}$ implies a change of the effective masses. A minimal solution is found with $m_d = 450$ MeV, $m_s = 1530$ MeV, $m_{\bar{Q}} = 4860$ MeV, and all $A_{ij} = 0$, except for $A_{ub} = 53$ MeV by fitting the spin-averaged ground-state masses of $(cc)$, $(c\bar{Q})$, $(cq)$ and the $c \rightarrow b$ analogues.

\[\text{footnote:} \] Of course, in case of identical quarks, the Pauli principle can induce some isospin dependence from the spin dependence. This is the reason why the $A$ baryon is lighter than the $\Sigma$ one. But here, this effect is not present, as isospin is carried by a quark and an antiquark.
A slightly better agreement is found by allowing both \( A_{cc} \) or \( A_{bb} \) to be non-zero, but we shall keep the minimal solution.

We use the basis defined in [19], namely

\[
\alpha_1 = (q_1 \bar{q}_3)^1_1 \otimes (q_2 \bar{q}_4)^1_1, \quad \alpha_2 = (q_1 \bar{q}_3)^1_1 \otimes (q_2 \bar{q}_4)^3_1, \\
\alpha_3 = (q_1 \bar{q}_3)^1_1 \otimes (q_2 \bar{q}_4)^3_3, \quad \alpha_4 = (q_1 \bar{q}_3)^1_1 \otimes (q_2 \bar{q}_4)^3_1, \\
\alpha_5 = (q_1 \bar{q}_3)^3_8 \otimes (q_2 \bar{q}_4)^1_0, \quad \alpha_6 = (q_1 \bar{q}_3)^3_8 \otimes (q_2 \bar{q}_4)^3_1, \\
\]

where the superscript denotes the colour 1 or 8, and the subscript 0 or 1 denotes the spin, with an overall recoupling to a colour-singlet \( J^P = 1^+ \) state.

The matrix elements of the colour-magnetic part have been given in [19], and are reminded in Table 1 for completeness.

One should now supplement it by the matrix elements of the chromo-electric term, which are

\[
H_{CE} = \begin{pmatrix}
X_0 & 0 & 0 & 0 \\
0 & X_0 & 0 & 0 \\
0 & 0 & X_0 & 0 \\
0 & 0 & 0 & X_0
\end{pmatrix},
\]

(7)

with

\[
X_0 = -\frac{16}{3}(A_{13} + A_{24}), \\
X_0 = \frac{4\sqrt{2}}{3}(A_{12} + A_{34} - A_{14} - A_{23}), \\
X_0 = \frac{2(A_{13} + A_{24}) - 4(A_{12} + A_{34}) - 14(A_{14} + A_{23})}{3}.
\]

(8)

The parameters are summarized in Table 2.

The ground-state masses of heavy quarkonia and heavy light mesons obtained using these parameters are listed in Table 3.
reasonable choice for a pairwise interaction, as a colour-singlet exchange would confine everything together. But multi-body forces could be envisaged in more complicated models.

5. Summary and conclusions

In this article, it was reminded that a simple quark model\cite{19} predicted the existence of an $I=1$ partner of the $X(3872)$ at the right mass and thus anticipated the recent discovery by BES III, Belle and CLEO-c \cite{1–3}. The model consisted of effective masses and a chromomagnetic interaction. It can be supplemented by a minimal chromoelectric term and then applied to the sector of states with hidden-beauty.

The model predicts a nearly degenerate quartet (an $I=0$ singlet and an $I=1$ triplet, with some mixing of the neutrals) near 10.62 MeV. The charged states are possible candidates for either the $Z_b(10610)^{±}$ or $Z_b(10650)^{±}$ states of Belle \cite{4}. It is, however, very difficult in this approach to produce an isospin $I=1$ state without a nearby $I=0$ partner, and to arrange two nearly degenerate isotriplets.

It seems important to use the most advanced accelerators and detectors to investigate this sector of hadron physics. The Belle II facility \cite{28} will of course provide us with crucial information. But the search is already active at the LHC, with in particular, a very recent search for the $X_b$ by the CMS Collaboration \cite{29}, with no evidence in the $\Upsilon(1S)\pi^+\pi^-$ channel. It is hoped that the combined efforts at lepton and hadron colliders will definitely clarify the situation in the hidden-beauty sector.

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References


