$X(3872)$ tetraquarks in B and B_s decays

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We discuss how the latest data on $X(3872)$ in B and B_s decays speak about its tetraquark nature. The established decay pattern, including the up-to-date observations by CMS, are explained by the mixing of two quasidegenerate, unresolvable neutral states. The same mechanism also explains isospin violations in X decays and strongly suggests that the lurking charged partners are required to have very small branching fractions in $J/\psi\rho^{\pm}$, well below the current experimental limits. In addition, a new prediction on the decay into $J/\psi\omega$ final states is attained. The newest experimental observations are found to give thrust to the simplest tetraquark picture and call for a definitive, in-depth study of final states with charged ρ mesons.

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The discussion on the nature of $X(3872)$ has been going on, with conflicting conclusions, for about two decades since its first observation at Belle [1].

The $X(3872)$ is first of all a remarkable example of fine-tuning realized in physics. Its mass is nearly equal to the sum of D^0 and $\bar{D}^{0*}$ open-charm mesons masses, whose composition of quantum numbers matches the $J^{PC} = 1^{++}$ assigned to the $X(3872)$. This feature is not met at the same level by any of the so-called exotic resonances discovered over the years. Reviews on exotic hadrons can be found in [2–8].

Despite its decay modes involving the J/Ψ, $X(3872)$ cannot be interpreted as a pure charmonium state. One of the simplest reasons for this is the fact that it decays in $J/\psi\rho$ and $J/\psi\omega$ with similar rates, thus violating isospin.

The proximity of the $X(3872)$ to the $D^0\bar{D}^{0*}$ threshold, isospin violations, and the lack of evidence so far of a complete multiplet of charged and neutral states has convinced a large part of the community working on this problem that the $X(3872)$ should be a sort of deuteron made of neutral D mesons, namely a $D^0\bar{D}^{0*}$ molecule, with a very small binding energy, which is still unknown because of the uncertainties in the determination of the $X(3872)$ mass value. On the other hand, the $X(3872)$ is produced, with a very large cross section, at proton-(anti) proton colliders in regions of transverse momenta of final state hadrons, which are too high (above $p_T \sim 15$ GeV) for the formation of such a loosely bound molecule [9,10]; see also [11].

Alternatively one might suppose that only color forces determine the structure of the $X(3872)$, which is often referred as to the compact tetraquark interpretation. Loosely bound molecules and compact tetraquarks are the two opposite extrema of a spectrum of more complex solutions that the problem may have. This is not to mention that some authors consider the possibility that the X might simply be a threshold kinematical effect, a cusp, as detailed in [12]. Another interesting suggestion, pursued by Voloshin and collaborators (see for example [13]), is that of hadrocharmonia, i.e., relatively compact charmonia embedded in a light quark mesonic excitation.

The compact tetraquark model was developed in [14–16]. It proposes that $X(3872)$ belongs to a complex of four-quark bound states: X_u, X_d, and $X^{\pm} = [cu][\bar{c}\,\bar{d}], [cd][\bar{c}\,\bar{u}]$, where parentheses mark diquark correlations.

Such states are expected to be very close in mass to each other. In a first estimate, Ref. [14] gave a $X_d - X_u$

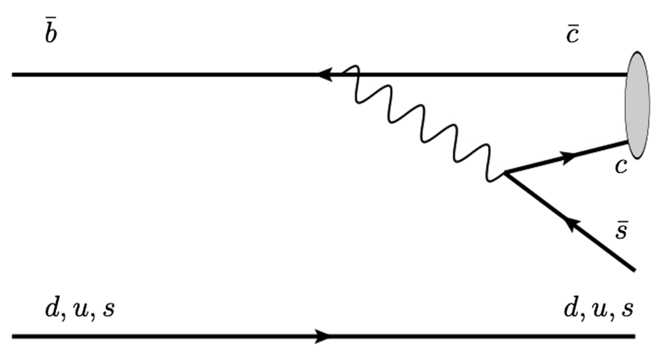

FIG. 1. The valence quarks in B and B_s decays. A pair of sea quarks is formed in the blob to generate the X tetraquarks.

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separation close to $2(m_d - m_u) \sim 7$ MeV. However, a second state close to $X(3872)$ has not been observed, and upper bounds have been given for the branching ratios of B meson decays into $X^\pm$ [17,18]. Building on the analysis of isospin breaking hadron masses [19,20], which takes into account the effect of the electromagnetic interactions, it was suggested [16] that X_u and X_d are much closer in mass than expected, so as to be two unresolved lines inside the $J/\psi\pi^+\pi^-$ peak. This quasidegeneracy is reached assuming a separation of scales between the diquark size and the size of the whole diquark-antidiquark composite state, also considered in [21]. To the best of our knowledge, the possibility of a diquark-antidiquark repulsion was first mentioned by Selem and Wilczek in [22]. Another result obtained in [16] was that X_u-X_d mixing, estimated from the branching ratios of $X(3872) \to J/\psi + 2\pi$ or 3π, would push the branching ratio for the production of $X^\pm$ in B meson decays well below the experimental limits of [17,18], thus calling for more refined searches.

CMS has recently reported [23] a determination of the branching ratio of the weak decay

$$\mathcal{B}(B_s^0 \to \phi X(3872) \to \phi J/\psi\pi^+\pi^-) = (4.14 \pm 0.54(\mathrm{stat}) \pm 0.32(\mathrm{syst}) \pm 0.46(\mathcal{B})) \times 10^{-6}. \tag{1}$$

Comparing it to other similar decays, the following pattern is observed [23,24]:

$$\mathcal{B}(B_s^0 \to \phi X \to \phi J/\psi\pi^+\pi^-) \simeq \mathcal{B}(B^0 \to K^0 X \to K^0 J/\psi\pi^+\pi^-) \simeq \frac{1}{2}\mathcal{B}(B^+ \to K^+ X \to K^+ J/\psi\pi^+\pi^-). \tag{2}$$

We will show how this pattern clearly emerges from the simplest decay diagram in Fig. 1 in the compact tetraquark picture of the $X(3872)$. In addition, the pattern in Eqs. (1) and (2), combined with our previous analysis [16] of the branching fractions of $X(3872) \to J/\psi + 2\pi/3\pi$, allows one to determine uniquely mixing and couplings of the two tetraquarks $X_u = [cu][\bar{c}\,\bar{u}]$, $X_d = [cd][\bar{c}\,\bar{d}]$. From these results we derive two new predictions:

(1) The branching ratio of the decays of B mesons into $J/\psi + 3\pi$,

$$R_{3\pi}^{+0} = \frac{\mathcal{B}(B^+ \to K^+ X(3872) \to K^+ J/\psi\pi^+\pi^-\pi^0)}{\mathcal{B}(B^0 \to K^0 X(3872) \to K^0 J/\psi\pi^+\pi^-\pi^0)} = 0.87 \pm 0.06. \tag{3}$$

(2) A definite range for the production of the charged tetraquark $X^\pm$ in B decays,[1]

$$0.05 < R_{2\pi}^- = \frac{\mathcal{B}(B^0 \to K^+ X(3872)^- \to K^+ J/\psi\pi^0\pi^-)}{\mathcal{B}(B^0 \to K^0 X(3872) \to K^0 J/\psi\pi^+\pi^-)} < 0.57, \tag{4}$$

to be compared with the present limit $R_{2\pi}^- < 1$ [25]. These predictions can be tested experimentally and, if supported, would provide a decisive clarification on the nature of the $X(3872)$.

Assuming a tetraquark $X(3872)$, in the blob of Fig. 1 one has to create a light quark pair from the sea. The overall weak decay is

$$(\bar{b} + u, d, s)_{B^+, B^0, B_s} \to \bar{c} + c\bar{s} + (d\bar{d} \text{ or } u\bar{u})_{\mathrm{sea}} + u, d, s.$$

The decays $B^{0,+} \to X K^{0,+}$ are then described by two amplitudes: A_1, where the $\bar{s}$ forms the kaon with the spectator u or d quark, and A_2, where it forms the kaon with a d or u quark from the sea. In terms of the unmixed states

$$\begin{aligned}
&\mathcal{A}(B^0 \to X_d K^0) \sim A_1 + A_2, \\
&\mathcal{A}(B^0 \to X_u K^0) \sim A_1, \\
&\mathcal{A}(B^0 \to X^- K^+) \sim A_2
\end{aligned} \tag{5}$$

and

[1] In the loosely bound molecular model, X(3872) has no charged partners, see, e.g., Ref. [5].

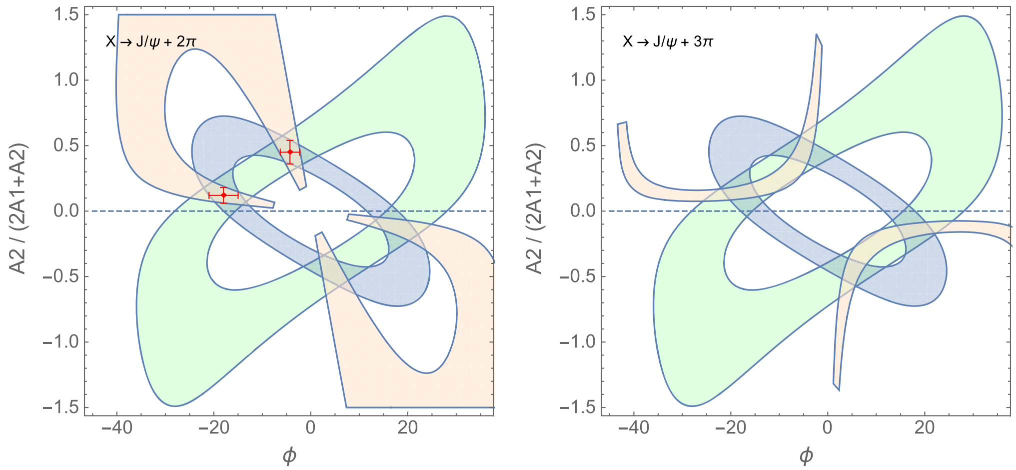

FIG. 2. Left panel: intersecting regions in the ϕ-z plane corresponding to the observed $R_{2\pi}^{+0}$, $R(B^0)$, and $R(B^+)$ ratios. Right panel: same as for left panel for the $R_{3\pi}^{+0}$, $R(B^0)$, and $R(B^+)$ ratios.

$$\begin{aligned} &\mathcal{A}(B^+ \to X_d K^+) \sim A_1, \\ &\mathcal{A}(B^+ \to X_u K^+) \sim A_1 + A_2, \\ &\mathcal{A}(B^+ \to X^+ K^0) \sim A_2. \end{aligned} \tag{6}$$

With near degeneracy of $X_{u,d}$, even a small $q\bar{q}$ annihilation amplitude inside the tetraquark could produce sizable mixing. We consider the mass eigenstates in the isospin basis, namely

$$\begin{aligned} X_1 &= \cos\phi \frac{X_u + X_d}{\sqrt{2}} + \sin\phi \frac{X_u - X_d}{\sqrt{2}}, \\ X_2 &= -\sin\phi \frac{X_u + X_d}{\sqrt{2}} + \cos\phi \frac{X_u - X_d}{\sqrt{2}} \end{aligned} \tag{7}$$

(we can take $\cos\phi > 0$, so that $-\pi/4 < \phi < +\pi/4$). It is straightforward[2] to compute the rate for B going to $X(3872)$, the sum of two unresolved, almost degenerate lines, followed by decay into $J/\psi + 2\pi/3\pi$, as a function of the mixing angle ϕ and of the ratio of the isospin zero and isospin 1 amplitudes $2A_1 + A_2$, A_2, respectively. The result [16] is reported in the two panels of Fig. 2 by the donut-shaped regions, which correspond to the experimental values of the two ratios [25],

$$R(B^0) = \frac{\Gamma(B^0 \to K^0 X(3872) \to K^0 J/\psi 3\pi)}{\Gamma(B^0 \to K^0 X(3872) \to K^0 J/\psi 2\pi)} = 1.4 \pm 0.6, \tag{8}$$

$$R(B^+) = \frac{\Gamma(B^+ \to K^+ X(3872) \to K^+ J/\psi 3\pi)}{\Gamma(B^+ \to K^+ X(3872) \to K^+ J/\psi 2\pi)} = 0.7 \pm 0.4. \tag{9}$$

Let us now turn to the results of Eqs. (1) and (2). From Eqs. (5)–(7), and recalling that

$$\mathcal{A}(X_{1,2} \to J/\psi\rho) = \sin\phi, \cos\phi, \tag{10}$$

one easily finds the ratio of the B^+ to B^0 rates in Eq. (2). The result is

$$\begin{aligned} R_{2\pi}^{+0} &= \frac{\mathcal{B}(B^+ \to K^+ X(3872) \to K^+ J/\psi \pi^+\pi^-)}{\mathcal{B}(B^0 \to K^0 X(3872) \to K^+ J/\psi \pi^+\pi^-)} \\ &= \frac{1 + 3z^2 - (1 - z^2)\cos(4\phi) - 2z\sin(4\phi)}{1 + 3z^2 - (1 - z^2)\cos(4\phi) + 2z\sin(4\phi)}, \end{aligned}$$

$$\text{where} \quad z = \frac{A_2}{2A_1 + A_2}. \tag{11}$$

A few observations are in order:

(1) We have summed over the rates of X_1 and X_2, as required by the hypothesis [16] that the two neutral states are both within the $J/\psi\rho$ width.
(2) $R_{2\pi}^{+0} = 1$ if either ϕ or z vanish, see Eqs. (5) and (6).
(3) The periodicity in ϕ of Eq. (12) is $\pi/2$, coinciding with the range of physically different configurations in Eq. (7).
(4) $2A_1 + A_2$ and A_2 correspond to isospin 0,1 and their relative sign is inessential; we may take $z > 0$ by convention.

Using the experimental branching ratios [25] and adding errors in quadrature, we find

$$R_{2\pi}^{+0} = 2.0 \pm 0.6. \tag{12}$$

[2]In Eqs. (18) and (19) of Ref. [16], one should correct the typo: $p_\rho/p_\omega \to p_\omega/p_\rho$.

The corresponding region in ϕ, z space is reported in Fig. 2, left panel. Equation (12) is in remarkable agreement with the previous determination based on the 2π vs 3π decays. It leads to the two solutions marked with points and bars in Fig. 2, left panel,[3]

$$\begin{aligned} &\text{Solution 1: } \phi = -18° \pm 3°, \qquad z = 0.12 \pm 0.06, \\ &\text{Solution 2: } \phi = -4.3° \pm 2°, \qquad z = 0.45 \pm 0.09. \end{aligned} \tag{13}$$

For B_s^0 decay, only the spectator quark can lead to the ϕ meson in the final state. The decay is described by one amplitude, A_3, with the same role as A_1 in B^0 decay,

$$R_{2\pi}^{s0} = \frac{\mathcal{B}(B_s \to \phi X(3872) \to \phi J/\psi \pi^+\pi^-)}{\mathcal{B}(B^0 \to K^0 X(3872) \to K^+ J/\psi \pi^+\pi^-)} = \left(\frac{A_3}{A_1 + A_2/2}\right)^2 \frac{2\sin(2\phi)^2}{1 + 3z^2 - (1 - z^2)\cos(4\phi) + 2z\sin(4\phi)}. \tag{14}$$

From Eqs. (13) and (14) we find

$$\begin{aligned} R_{2\pi}^{s0}(\text{Solution 1}) &= \left(\frac{A_3/A_1}{1.14}\right)^2 \times 1.35 = 1 \quad \text{for } A_3/A_1 = 0.97, \\ R_{2\pi}^{s0}(\text{Solution 1}) &= \left(\frac{A_3/A_1}{1.82}\right)^2 \times 0.08 = 1 \quad \text{for } A_3/A_1 = 6.5. \end{aligned} \tag{15}$$

On the other hand, the near equality of the branching ratios [25]

$$\begin{aligned} \mathcal{B}(B^0 \to K^{*0} X(3872) \to K^{*0} J/\psi \pi^+\pi^-) &= (4.0 \pm 1.5) \times 10^{-6}, \\ \mathcal{B}(B^0 \to K^0 X(3872) \to K^0 J/\psi \pi^+\pi^-) &= (4.3 \pm 1.3) \times 10^{-6} \end{aligned} \tag{16}$$

suggests that the couplings $A_{3,4}$ for B decay into vector mesons are similar to $A_{1,2}$ of Eqs. (5) and (6). Barring unforeseen cancellations, we may conclude that the CMS pattern in Eq. (2) selects solution 1 over solution 2.[4] This fact has a simple interpretation. In solution 1, z is small and the mixing is such that the contribution of X_u dominates in B^0 decay. Thus, to a good approximation, meson formation in B^0 decay is dominated by the spectator quark as in B_s decay.

Using the parameters of solution 1, one obtains the two predictions in Eqs. (3) and (4). We conclude that the new results by CMS mark an advancement in the understanding of the $X(3872)$ problem and call for a few more steps to do on the experimental side to safely decide among existing interpretations.

[3] The solutions with $z < 0$ are simply reflections of $z > 0$ ones and do not correspond to physically different solutions.

[4] A quantitative conclusion can be found by determining $A_{3,4}$ from the decays $B \to K^* X(3872) \to K^* J/\psi \pi^+\pi^-$ as done here for decays into K mesons. The branching ratio of the decay $B^+ \to K^{*+} X(3872)$ is not available at present [25].

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