Belle II and XYZ hadrons

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Abstract

We present a schematic review on those measurements to be considered for the Belle II physics program to improve the understanding on the nature of XYZ exotic resonances – some of them may have roles in discriminating between proposed theoretical models.

Belle II, could provide a number of precision measurements to challenge the molecular picture of the $X(3872)$ and other Y, Z resonances which are susceptible of any molecular interpretation. It can equally be the test table of the compact tetraquark models, the diquark-antidiquark one being one possible realization [6, 7].

1. ***Loosely bound molecules.*** A precise experimental determination of the binding energy ε

   $$\varepsilon = m_D + m_{D^*} - m_X \gtrsim 0 \tag{1}$$

   total width Γ_X and $\mathcal{B}(X \to DD\pi)$ branching fraction, would constrain the loosely bound hadron molecule picture of $X(3872)$ or any Y, Z molecular candidates.

   In the case of the X, for the time being, we only know that $\Gamma_X \lesssim 1.2$ MeV and $\mathcal{B}(X \to DD\pi) > 32\%$ (from PDG) with $m_X = 3871.69 \pm 0.17$ MeV – precise determination of D and D^* masses enter in the determination of the binding energy ε as well. The most recent measurement of $m_{D^0} - m_{D^{*0}}$ by Tomaradze *et al.* [8] leads to a binding energy of $\varepsilon \sim 3 \pm 192$ keV in the $D\bar{D}^*$ molecule interpretation of $X(3872)$.

   On the other hand we can show that ε is related to the strong coupling g, appearing in the $X \to DD^*$ partial width, through

   $$\varepsilon \simeq \frac{g^4}{512\pi^2}\frac{m^5}{m_D^4 m_{D^*}^4} \tag{2}$$

   which is independent on whatever interaction potential could be responsible for the DD^* coalescence into a loosely bound molecule (m is the reduced mass of the DD^* system).

   This relation therefore clearly relates the binding energy, the $X \to DD^*$ branching ratio, and the total width of the X. An accurate determination of the X lineshape would provide the total width Γ_X and mass m_X. The latter, combined with more precise measurements on the D and D^* masses from the LHC, might allow to reach a nonzero value for ε. If these three observables respect (2) to some extent, this result would strongly call for an explanation of X coalescence from DD^* in proton-proton collisions observed at high p_T cuts because formula (2) assumes necessarily $\varepsilon \approx T$, the latter being the kinetic energy within the DD^* pair. If (2) is manifestly violated, the X loosely bound picture should be reconsidered. In principle compact tetraquarks can be produced in high energy hadron collisions in the same way as standard mesons and baryons.

2. ***Lineshape of X.*** The study of the X lineshape can be performed through the invariant mass analysis of X decay products of the channels known up to now, in the decay process $B \to KX$. The best channel to measure mass and width is the usual $X \to J/\psi\,\pi^+\pi^-$. In order to access also the absolute branching ratios, a precise measurement of the K momentum distribution in $B \to KX_{c\bar{c}}$ is needed. Such an analysis has already been performed in the past by BaBar, with a limited integrated luminosity of 211 fb^{-1} [9], and can significantly be improved at Belle II.

   An independent, even if statistically challenging, way to study the X lineshape at Belle II could proceed through the process [10]:

   $$e^+e^- \to \gamma_{\text{ISR}}\, Y(4260) \to \gamma_{\text{ISR}}\, X(3872)\gamma \tag{3}$$

where the first ISR photon allows to reach the $Y(4260)$ from the $\Upsilon(5S)$ com e^+e^- energy. A good resolution on E_γ might allow a precise reconstruction of the X lineshape. Both photons need to be tagged, the ISR one being peaked at very small angles w.r.t. the beam line. A detailed investigation of the radiative Bhabha scattering background will be needed.

As for the decay in open charm, a detailed study of $X(3872) \to D^0\overline{D}^0\pi^0$ and $X(3872) \to D^0\overline{D}^0\gamma$ without constraining an on-shell D^{*0}, is needed to measure the unbiased lineshape. This is required to distinguish between a molecular X which has to lie below threshold, and an above-threshold "virtual state". The predictions in Ref. [11] on the asymmetric lineshape can be verified.

3. **$X(3872) \to J/\psi\omega$ *decay channel.*** A precise measurement of the $X(3872) \to J/\psi\omega$ branching fraction is important to constrain the predictions about the isospin breaking in $X(3872)$. Moreover, since the analysis in [12] favored a 2^{-+} assignment for the $X(3872)$, it is interesting to have an independent measurement to confirm the 1^{++} signature in the same channel.

4. ***Charged partners of* X.** In some tetraquark models, the $X^{\pm}(\approx 3872)$ might be very broad resonances. The upper limits established up to now are not very conclusive. It is important to set more constrained limits on the existence of these states as well as to seek all the charged/neutral missing components of Y, Z particles to distinguish between complete and incomplete charge multiplets.

5. ***Z_cs and Z_bs.*** The binding energies of (charged) tetraquarks Z_cs [13–15] and Z_bs [16] should be measured with high precision as well. Positive values of $B = -\varepsilon$ as defined above in (1) are clearly not acceptable to describe a bound molecule of hadrons.

   Negative values of B values should again be confronted with branching ratios into candidate molecular components and total widths, so as to verify (2).

   Data available give the binding energies $B = -\varepsilon$ in Table 1

Resonance	Threshold	B
$Z_b(10610)^+$	BB^*	2.6 ± 2.0 MeV
$Z_b'(10650)^+$	B^*B^*	1.8 ± 1.6 MeV
$Z_c(3900)^+$	DD^*	12.9 ± 3.4 MeV
$Z_c'(4020)^+$	D^*D^*	6.7 ± 2.4 MeV

Table 1: All these entries have $B > 0$. Precision measurements are necessary to definitely assess if any of these states has $B < 0$, *i.e.* a candidate molecular state.

Another interesting information comes from the mass difference between $Z^{(\prime)}$ and Z states as it is related to the chromomagnetic couplings of the diquark-antidiquark model [17]

$$M(Z_b') - M(Z_b) = 45 \text{ MeV} = 2\kappa_b \tag{4}$$

$$M(Z_c') - M(Z_c) = 120 \text{ MeV} = 2\kappa_c \tag{5}$$

$$\kappa_b : \kappa_c = M_c : M_b \approx 0.30 \tag{6}$$

the latter equation suggesting, $2\kappa_b \approx 36$ MeV to be compared with the experimental determination of 45 MeV. Moreover, in order to understand whether the $Z_c^{(\prime)}$ states are produced in $Y(4260)$ decays, a proper study of the $e^+e^- \to \gamma_{\rm ISR}(J/\psi, h_c)\pi^+\pi^-$ channel as a function of $E_{\rm ISR}$ is needed.

The decay pattern of $Z_c^{(\prime)}$ may shed light on the their nature. As shown in [18], the diquark-antidiquark and the molecular picture make different predictions for the decay $Z_c^{(\prime)} \to \eta_c\rho$. The former predicts branching fractions comparable with or greater than that in the discovery modes, the latter predicts branching fractions two orders of magnitude smaller. Moreover, the molecular picture predicts a sizeable component of $Z_c^\prime \to J/\psi\pi$, which has not been observed yet.

It is worth looking for isospin violating channels, such as $Z_c^{(\prime)} \to J/\psi\eta$ and $\to \eta_c\,\omega$, which could favor a tetraquark assignment.

6. ***$Z(4430)$* and *$Z(4200)$*.** This state has been discovered by Belle [19], and recently confirmed by LHCb [20]. Its molecular description is still unclear, being this state far from ground-state open charm mesons. However, it has been proposed that the $Z(4430)$ could be a molecule made up of a D (D^*) meson, and of the radially excited $D^*(2600)$ ($D(2550)$) [21]. These two radial excitations has been found by BaBar and LHCb [22], but the errors on masses and widths are still too large to establish the binding energy and check the molecular hypothesis. More precise data on these states are needed, as well as a direct search of $B \to Z(4430)K \to \overline{D}D^*(2600)K$, or $B \to Z(4430)K \to \overline{D}^*D(2550)K$. On the other hand, this state has a clear interpretation within the tetraquark model as the radial excitation of the $Z_c(3900)$ [7]. In this case, a sizeable branching fraction $B \to Z(4430)K \to \overline{D}D^*K$ is naturally expected. A similar analysis of $B \to Z(4200)K \to \overline{D}D^*K$ could help in understanding the nature of the recently discovered $Z(4200)$.

7. ***The Y states.*** The Y are 1^{--} resonances discovered in $e^+e^- \to \gamma_{\rm ISR}\,(c\bar{c})\,\pi^+\pi^-$, with $(c\bar{c}) = J/\psi, \psi^\prime, h_c$. It is puzzling that none of these states have been found in other production or decay mechanisms, in particular in open charm final states as expected for vector charmonia (see for example [23]). These states can be identified as P-wave orbitally excited tetraquarks [6], which predicts a specific pattern of radiative decays into ground-state tetraquarks (see table 2), For example, the decay $Y(4260) \to \gamma X(3872)$ seen by BES [10] enforces this interpretation. Studying radiative decays of resonances like the $Y(4630)$ and $Y(4220)$ could allow to discover the predicted tensor X_2 particle (if not identified with the $Z(3930)$), and the scalar one X_0. Finally, to check this picture, a higher statistics in the analysis of $e^+e^- \to \gamma_{\rm ISR}\,J/\psi\pi^+\pi^-$ should show hints of the four states reported in Table 2. We stress that branching ratio $BR\,(Y(4630) \to J/\psi\pi^+\pi^-)$ might be very small, being the state dominated by the baryonic decay $\Lambda_c^+\Lambda_c^-$, as expected for a tetraquark.

   The molecular interpretation requires instead an *ad hoc* identification for each of these states. No Y states has been observed in other mechanisms but ISR production. A systematic search in $B \to YK \to (c\bar{c})\pi^+\pi^-K$ decays is interesting, because the absence of such decays would require more exotic explanations. The existing upper limit for $B^+ \to Y(4260)K^+ \to J/\psi\pi^+\pi^-K^+$ by BaBar [24] is not compelling enough and can be significantly improved.

8. ***$Y(4260)$* *at Belle.*** Despite many searches, the $Y(4260)$ has been observed only in $J/\psi\pi\pi$ final state. Its large width $\Gamma = (120 \pm 12)\,\text{MeV}$, is still poorly understood if no open charm decay occur. In addition to the tetraquark interpretation, the $Y(4260)$ has been also explained as a

State	$P(S_{c\bar{c}}=1):P(S_{c\bar{c}}=0)$	Assignment	Radiative Decay
Y_1	3:1	$Y(4008)$	$\gamma+X_0$
Y_2	1:0	$Y(4260)$	$\gamma+X(3872)$
Y_3	1:3	$Y(4220)$	$\gamma+X_0'=\gamma+X(3915)$?
Y_4	1:0	$Y(4630)$	$\gamma+X_2=\gamma+Z(3930)$?

Table 2: The relative probability of having $s_{c\bar{c}}=1$ versus $s_{c\bar{c}}=0$ in the decay product of $L=1$ tetraquarks. Radiative decays are the natural $E1$ transitions, enforcing heavy quark spin conservation. Here we propose the tentative assignment $X_0'=X(3915)$ and $X_2=Z(3930)$.

$DD_1(2420)$ loosely bound molecule [25], which predicts its dominant decay to be $Y(4260)\to DD^*\pi$. A study of the channel $e^+e^-\to\gamma_{\rm ISR}DD^*\pi$ improving old Belle analysis [26] will be crucial to shed light on this unresolved controversy.

9. $Y(4220)$ ***from BES to Belle.*** A reanalysis of BES $e^+e^-\to h_c\pi^+\pi^-$ data [27] has provided some evidence of a vector state $Y(4220)$, which is expected in the tetraquark model [7, 28]. Belle II is able to produce a deeper analysis of $e^+e^-\to\gamma_{\rm ISR}\,h_c\pi^+\pi^-$, with a more detailed binning in $m_{h_c\pi\pi}$, in order to confirm the existence of this state.

10. ***Apparent heavy spin violating decays.*** Some decays as

$$\Upsilon(10890)(\Upsilon(5S))\to Z_b^{(\prime)}\pi\to h_b(nP)\pi\pi \tag{7}$$

can be suspected to violate heavy quark spin – the initial state having $S_{b\bar{b}}=1$ whereas h_b has $S_{b\bar{b}}=0$. This is not so in the diquark-antidiquark model because the intermediate state $Z_b^{(\prime)}$ contains a superposition of $S_{b\bar{b}}=0,1$. The coefficients of this superposition could precisely be measured at Belle II

$$Z_b=\frac{\alpha|1_{q\bar{q}},0_{b\bar{b}}\rangle-\beta|0_{q\bar{q}},1_{b\bar{b}}\rangle}{\sqrt{2}} \tag{8}$$

$$Z_b'=\frac{\beta|1_{q\bar{q}},0_{b\bar{b}}\rangle+\alpha|0_{q\bar{q}},1_{b\bar{b}}\rangle}{\sqrt{2}} \tag{9}$$

from data on $1_{b\bar{b}}\to 0_{b\bar{b}}$ transitions

$$\begin{aligned} g_Z &= g(\Upsilon\to Z_b\pi)g(Z_b\to h_b\pi)\propto -\alpha\beta^*\langle h_b|1_{q\bar{q}},0_{b\bar{b}}\rangle\langle 0_{q\bar{q}},1_{b\bar{b}}|\Upsilon\rangle \\ g_{Z'} &= g(\Upsilon\to Z_b'\pi)g(Z_b'\to h_b\pi)\propto \alpha^*\beta\langle h_b|1_{q\bar{q}},0_{b\bar{b}}\rangle\langle 0_{q\bar{q}},1_{b\bar{b}}|\Upsilon\rangle \end{aligned} \tag{10}$$

(requiring $g_Z=-g_Z'$) and from those on $1_{b\bar{b}}\to 1_{b\bar{b}}$ transitions such as

$$\begin{aligned} f_Z &= f(\Upsilon\to Z_b\pi)f(Z_b\to\Upsilon(nS)\pi)\propto|\beta|^2\langle\Upsilon(nS)|0_{q\bar{q}},1_{b\bar{b}}\rangle\langle 0_{q\bar{q}},1_{b\bar{b}}|\Upsilon\rangle \\ f_{Z'} &= f(\Upsilon\to Z_b'\pi)f(Z_b'\to\Upsilon(nS)\pi)\propto|\alpha|^2\langle\Upsilon(nS)|0_{q\bar{q}},1_{b\bar{b}}\rangle\langle 0_{q\bar{q}},1_{b\bar{b}}|\Upsilon\rangle \end{aligned}$$

An experimental determination of these effective couplings can be drawn already from Belle data [29] which allows to roughly determine $|\alpha|^2/|\beta^2|$ and the product $|\alpha\beta|$

$$|\alpha|^2/|\beta|^2=0.85\pm0.08 \tag{11}$$

and

$$|\alpha\beta| = 1.4 \pm 0.3 \tag{12}$$

which gives an indication of $\alpha \approx \beta \approx 1$. The relative phase between the Z_b and Z_b' contributions has also been measured both in $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ and $\Upsilon(5S) \to h_b(mP)\pi^+\pi^-$ transitions with a value of $(-8 \pm 10)^\circ$ in the $1_{b\bar{b}} \to 1_{b\bar{b}}$ decays and $(185 \pm 42)^\circ$ in the $1_{b\bar{b}} \to 0_{b\bar{b}}$ decays, which agrees fairly well with (8) and (9) with $\alpha \approx \beta \approx 1$. A precise determination of this conclusion would be very valuable for the assessment of the diquark-antidiquark picture of Z states.

A quantitative analysis of the Belle II data including both direct and resonant components (i.e., via the intermediate resonant states Z_b and Z_b') is required to test the underlying dynamics.

11. ***Search for tetraquarks in $\gamma\gamma$ fusion.*** The so-called $\gamma\gamma$ fusion technique can be resolutive to seek the expected spin-even states in the $3700 - 4100$ MeV region. The lowest lying scalar tetraquark X_0 could be found in the scattering channel $\gamma\gamma \to \eta_c\pi$ if isovector, or $\to \eta_c\eta$ if isosinglet, since it is predicted to be below the $J/\psi\rho$ threshold. The scalar X_0' and the tensor X_2 could be found also in $\gamma\gamma \to J/\psi\rho$ and $\to J/\psi\omega$. The same technique could be applied to look for the lowest lying scalar molecule, decaying into $D\bar{D}$ [30].

12. $X(3915)$ ***at Belle.*** The $X(3915)$ resonance, observed in $B \to K\omega J/\psi$ and $\gamma\gamma \to \omega J/\psi$ [12, 31], has been recently identified as the ordinary $\chi_{c0}(2P)$. However, this assignment is not embraced by the whole community [32]. For example, no evidence of a resonant structure compatible with the $\chi_{c0}(2P)$ is found in the reaction $\gamma\gamma \to D\bar{D}$ [33]. If this resonance were found to be produced in $Y(4220) \to \gamma X(3915)$, this would be a strong evidence of its tetraquark nature.

13. ***Exotics in the B-sector at Belle.*** The exotic B-sector could be explored at Belle II. This opportunity opens the possibility to crosscheck both the tetraquark and the molecular pattern looking for the same exotic states appearing in the charm sector.

    Recently the Belle collaboration observed that the $\Upsilon(5S)$ decays preferably in BB^* and not in $B_s^{(*)}B_s^{(*)}$ mesons [34]. This non conventional feature would be accommodated interpreting this state as the analogue of the $Y(4260)$ tetraquark. This suggestion will be strengthened if, in contrast, the decays of the $\Upsilon(6S)$ in $B_s^{(*)}B_s^{(*)}$ were found.

    The X_b analogue of the $X(3872)$ has not been found in the $\Upsilon\pi^+\pi^-$ invariant mass distribution at LHC [35]. However, the Belle experiment has the possibility to spectacularly test the tetraquark model searching for the radiative decays of the $\Upsilon(5S)$ through $\Upsilon(5S) \to \gamma X_b \to \gamma\Upsilon(nS)\pi^+\pi^-(\pi^0)$ or $\Upsilon(5S) \to \gamma X_b \to \gamma B^0\bar{B}^{*0}$. The additional π^0 is needed if no isospin violation occurs in the $b\bar{b}$ sector.

    On the other hand, the research of loosely bound B-mesons molecules is crucial to test the whole molecular picture used to interpret the exotic states in the charm sector. In Table 3, starting from the interpretation of the exotics in the charm sector as molecules, we suggest a possible pattern that should be reasonably seen if this interpretation holds. We remark that, if the $Z(4430)$ were a $D^{(*)}D^{(*)}(2S)$ molecule, its $b\bar{b}$ partner would contain the undiscovered $B^{(*)}(2S)$ meson.

charmed molecule	Expected state	Threshold [MeV]
$X(3872) \sim DD^*$	$BB^*(X_b)$	10604.8 ± 0.4
$Y(4260) \sim DD_1$ [25]	BB_1	11003 ± 2
$Y(4660)/Y(4630) \sim \psi(2S)f_0$ [36]	$f_0\Upsilon(2S)$	11013 ± 20
$\eta_c(2S)f_0$ [37]	$\eta_b(2S)f_0$	10990 ± 20
$D_2(2460)K$ [38]	B_2K	6237 ± 5

Table 3: List of some molecular states expected to be close to some open bottom thresholds according to what found or predicted in the charm sector.

Summary

In Table 4 we summarize some of the interesting channels to be investigated at Belle II.

state	looking for	experimental channel
$X(3872)$	mass and width	$B \to XK \to J/\psi\pi^+\pi^-K$
	lineshape	$B \to XK,\ X \to (D^0\bar{D}^0\pi,\ D^0\bar{D}^0\gamma)$
	isospin violation	$B \to XK \to J/\psi\omega K$
	charged partners	$B \to X^\pm K \to J/\psi\pi^\pm\pi^0K$
$Z_c^{(\prime)}$	mass and binding energy	$e^+e^- \to \gamma_{\rm ISR}(J/\psi, h_c)\pi^+\pi^-$
	production mechanism	$e^+e^- \to \gamma_{\rm ISR}(J/\psi, h_c)\pi^+\pi^-$
	discriminating channel	$Z^{(\prime)} \to \eta_c\rho$
$Z_b^{(\prime)}$	mass and binding energy	$\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$
$Z(4430)$	open charm decay modes	$B \to Z(4430)K \to \bar{D}D^*(2600)K$
		$B \to Z(4430)K \to \bar{D}^*D(2550)K$
$Z(4200)/Z(4430)$		$B \to Z(4430)K \to \bar{D}D^*K$
Y states	tetraquark confirmation	$e^+e^- \to \gamma_{\rm ISR}\, J/\psi\pi^+\pi^-$
$Y(4260)$	open charm decay mode	$e^+e^- \to \gamma_{\rm ISR}DD^*\pi$
$Y(4220)$	confirmation	$e^+e^- \to \gamma_{\rm ISR}\, h_c\pi^+\pi^-$
$X(3915)$	tetraquark model prediction	$Y(4220) \to \gamma X_0' = \gamma X(3915)$?
	0^+, 2^+ isosinglet tetraquarks	$\gamma\gamma \to \eta_c\eta$, $\gamma\gamma \to J/\psi\omega$
	0^+, 2^+ isovector tetraquarks	$\gamma\gamma \to \eta_c\pi$, $\gamma\gamma \to J/\psi\pi^+\pi^-$
	tetraquark radiative transitions	$Y(4630) \to \gamma X_2$, $Y(4008) \to \gamma X_0$
$\Upsilon(5S)$	tetraquark prediction	$\Upsilon(5S) \to \gamma X_b \to \gamma\Upsilon(nS)\pi^+\pi^-(\pi^0)$
		$\Upsilon(5S) \to \gamma X_b \to \gamma B^0\bar{B}^{*0}$
$\Upsilon(6S)$	bottom-strange decay modes	$\Upsilon(6S) \to B_s^{(*)}B_s^{(*)}$
X_b	production	$\Upsilon(5S) \to X_b\gamma \to \Upsilon(nS)\pi^+\pi^-\gamma$

Table 4: Summary of decay modes of interest to discuss molecules/tetraquarks.

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