Predictions for the Decays of $\bar{B}^0 \rightarrow \bar{K}^{*0} X (YZ)$
and $\bar{B}_s^0 \rightarrow \phi X (YZ)$ with $X (4160), Y (3940), Z (3930)$

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Outline

• Introduction and motivation
• Formalism
• Results of the ratios
• Complementary test of the molecular nature of the XYZ states
• Summary
Introduction and motivation

- The nature of the XYZ resonances is still unclear.
- Within the framework of the hidden gauge formalism:

Some XYZ states are dynamically generated from the V - V interaction, most notably the $D^*\bar{D}^*$ or $D_s^*\bar{D}_s^*$ states.

<table>
<thead>
<tr>
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[ R. Molina and E. Oset, Y(3940), Z(3930) and the X(4160) as dynamically generated resonances form the vector-vector interaction, PRD80(2009)114013 ]

These XYZ states are predicted to be molecular states.
The aim of this work:

• Study reactions where some $XYZ$ states can be procuced;

$$\bar{B}^0 \rightarrow \bar{K}^{*0} X (YZ), \quad \bar{B}_s^0 \rightarrow \phi X (YZ)$$

with $XYZ$ states generated dynamically from V-V interactions.

[ R. Molina and E. Oset, PRD80(2009)114013 ]

• Evaluate ratios for different decay modes.

• Propose a test linked to the molecular nature of some $XYZ$ resonances.
\[ \bar{B}_s^0 \to \phi R, \quad \bar{B}^0 \to K^{*0} R. \quad [R = X(4160), \ Y(3940), \ Z(3930)] \]

\[
\begin{pmatrix}
u \\ c \\ t \\ d \\ s \\ b
\end{pmatrix}
\]

Cabibbo favored transitions:
- \( b \to c \)
- \( c \to s \)

- **The Cabibbo favored dominant mechanism:**

![Diagram](image)

Fig. 1 \( \bar{B}_s^0 \) and \( \bar{B}^0 \) decays into \( c\bar{c} \) and a \( q\bar{q} \) pair.
Formalism

• Hadronization of ccbar:

Adding an extra $q\bar{q}$ pair with the quantum numbers of the vacuum,

A pair of vector mesons

\[
\bar{u}u + \bar{d}d + \bar{s}s + \bar{c}c
\]

Fig. 2 Hadronization of the $c\bar{c}$ pair into two vector mesons for $\bar{B}_s^0 (\bar{B}^0)$ decay.

$c\bar{c}$ pair is in $I = 0$  \rightarrow  V-V pair with $I=0$
Formalism

The $q\bar{q}$ matrix:

\[
M = \begin{pmatrix}
u u & ud & u\bar{s} & u\bar{c} \\
d\bar{u} & d\bar{d} & d\bar{s} & d\bar{c} \\
s\bar{u} & s\bar{d} & s\bar{s} & s\bar{c} \\
c\bar{u} & c\bar{d} & c\bar{s} & c\bar{c}
\end{pmatrix}
= \begin{pmatrix} u \\ d \\ s \\ c \end{pmatrix}
\begin{pmatrix}
u \\ d \\ s \\ c
\end{pmatrix}
\]

with the property $M \cdot M = M (\bar{u}u + \bar{d}d + \bar{s}s + \bar{c}c)$.

The matrix $M$ corresponds to the SU(4) vector matrix:

\[
V = \begin{pmatrix}
\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & \rho^+ & K^{*-} & \bar{D}^* \\
\rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & K^{*0} & D^- \\
K^{*-} & \bar{K}^{*0} & \phi & \bar{D}^*_s \\
D^{*0} & D^* & D_s^* & J/\psi
\end{pmatrix}
\]
Formalism

\[ c\bar{c}(\bar{u}u + \bar{d}d + \bar{s}s + \bar{c}c) \equiv (M \cdot M)_{44} \equiv (V \cdot V)_{44} \]

\[ (V \cdot V)_{44} = D^{*0} \bar{D}^{*0} + D^{*+} D^{*-} + D_{s}^{*+} D_{s}^{*-} + J/\psi J/\psi. \]

\[ (V \cdot V)_{44} \rightarrow \sqrt{2}(D^{*} \bar{D}^{*})^{I=0} + D_{s}^{*+} D_{s}^{*-}. \]

After the hadronization of the \( c\bar{c} \) pair, only the \( D^{*} \bar{D}^{*} \) and \( D_{s}^{*} \bar{D}_{s}^{*} \) with \( I = 0 \) can be produced.
Formalism

- FSI of the vector-vector mesons:

Fig. 3. Formation of $R(XYZ)$ through rescattering of $MM'(D^*\bar{D}^* \text{ or } D_s^*\bar{D}_s^*)$ and coupling to the resonance $R$.

Connect with the work of [R. Molina and E. Oset, PRD80(2009)114013], where four $XYZ$ states with $I=0$ were dynamically generated from $V$-$V$ interaction.
Formalism

- **XYZ states generated from V-V interaction:**

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These XYZ states are predicted to be molecular states.
Formalism

- Transition amplitude and the partial decay width:

Amplitude:
\[ t(\bar{B}_s^0 \rightarrow \phi R) = V_P(\sqrt{2}g_{D^*D^*},_R G_{D^*D^*} + g_{D^*_sD^*_s},_R G_{D^*_sD^*_s}) \]

\[ V_P : \] Different unknown constants, summarizing the production amplitude at tree level;

\[ G_{MM'} : \] the loop function of two vector meson propagators.

\[ G_i(s) = i \int \frac{d^4q}{(2\pi)^4} \frac{1}{(P - q)^2 - m_1^2 + i\varepsilon} \frac{1}{q^2 - m_2^2 + i\varepsilon}, \quad s = P^2 \]

\[ g_{MM',R} : \] the coupling of the resonance R to the MM' meson pair, taken from \[ [\text{R. Molina and E. Oset, PRD80(2009)114013}] \].

Similar formalism for \( \bar{B}^0 \rightarrow \bar{K}^{*0} R \).
**Formalism**

Partial decay width:

\[
\Gamma_{R_i} = \frac{1}{8\pi} \frac{1}{m_{\bar{B}_i}^2} |t_{\bar{B}_i^0 \rightarrow \phi (K^{*0}) R_i}|^2 P^{2L+1}_{\phi (K^{*0})},
\]

angular momentum \( L = \begin{cases} 
0, & \text{for } J^P = 1^+; \\
1, & \text{for } J^P = 0^+, 2^+.
\end{cases} \)

- **The ratios:** \((\text{the unknown constants } V_P \text{ are canceled})\)

\[
R_1 \equiv \frac{\Gamma_{\bar{B}_s^0 \rightarrow \phi R_1^{J=0}}}{\Gamma_{\bar{B}_s^0 \rightarrow K^{*0} R_1^{J=0}}}, \quad R_2 \equiv \frac{\Gamma_{\bar{B}_s^0 \rightarrow \phi R_2^{J=1}}}{\Gamma_{\bar{B}_s^0 \rightarrow K^{*0} R_2^{J=1}}},
\]

\[
R_3 \equiv \frac{\Gamma_{\bar{B}_s^0 \rightarrow \phi R_1^{J=2}}}{\Gamma_{\bar{B}_s^0 \rightarrow K^{*0} R_1^{J=2}}}, \quad R_4 \equiv \frac{\Gamma_{\bar{B}_s^0 \rightarrow \phi R_2^{J=2}}}{\Gamma_{\bar{B}_s^0 \rightarrow K^{*0} R_2^{J=2}}}, \quad R_5 \equiv \frac{\Gamma_{\bar{B}_s^0 \rightarrow \phi R_1^{J=2}}}{\Gamma_{\bar{B}_s^0 \rightarrow \phi R_2^{J=2}}},
\]

where \( R_1^{J=0}, R_1^{J=1}, R_1^{J=2} \) and \( R_2^{J=2} \) are the \( Y(3940), Y_P, \)
\( Z(3930) \) and \( X(4160) \), respectively.
Results for the ratios

\[ R_1 = 0.95, \quad R_2 = 0.96, \]
\[ R_3 = 0.95, \quad R_4 = 0.83, \quad R_5 = 0.84. \]

(without free parameters!)

- All the ratios are of the order of unity;
- The ratios \( R_1 \sim R_4 \) obtained are not determining the molecular nature of the resonances, but only on the fact that they are \( c\bar{c} \) based.
- The ratios \( R_5 \) is not just a phase space ratio, providing more information, since it involves two independent resonances.
  
  If only phase space, \( R_5 \approx 4. \)
Complementary test of the molecular nature of the $XYZ$ states

We study the decay $\bar{B}_s^0 \rightarrow \phi D^* \bar{D}^*$ or $\bar{B}_s^0 \rightarrow \phi D_s^* \bar{D}_s^*$ close to the $D^* \bar{D}^*$ and $D_s^* \bar{D}_s^*$ thresholds.

Fig. 4. Feynmann diagrams for the $D^* D^*$ production in $B_s^0$ decays.

\[ t(\bar{B}_s^0 \rightarrow \phi D^* \bar{D}^*) = V_P (\sqrt{2} + \sqrt{2} G_1 t_{(1\rightarrow1)} + G_2 t_{(2\rightarrow1)}) , \]

\[ t(\bar{B}_s^0 \rightarrow \phi D_s^* \bar{D}_s^*) = V_P (1 + \sqrt{2} G_1 t_{(1\rightarrow2)} + G_2 t_{(2\rightarrow2)}) \]

1: $D^* \bar{D}^*$; 2: $D_s^* \bar{D}_s^*$
Complementary test of the molecular nature of the XYZ states

The differential cross section for production:

$$\frac{d\Gamma}{dM_{\text{inv}}} = \frac{1}{32 \pi^3 M^2_{B_s}} p_{\phi} \tilde{p}_{D^*} |t(\bar{B}^0_s \rightarrow \phi D^* D^*)|^{2} p_{\phi}^{2L},$$

$$R_{\Gamma} = \frac{M^3_R}{p_{\phi} \tilde{p}_{D^*}} \frac{1}{\Gamma_R} \frac{d\Gamma}{dM_{\text{inv}}}$$

$$= \frac{M^3_R}{4\pi^2} \frac{p_{\phi}^{2L}(M_{\text{inv}})}{p_{\phi}^{2L+1}(M_R)} \left| \frac{t(\bar{B}^0_s \rightarrow \phi D^* D^*)}{t(\bar{B}^0 \rightarrow R\phi)} \right|^2,$$
• The ratios are different for each case and have some structure;

• There is a fall down of the differential cross sections as a function of energy, as it would correspond to the tail of a resonance below threshold.
**Summary**

- We have investigated the decays of $\bar{B}^0 \rightarrow K^* R$ and $\bar{B}_s^0 \rightarrow \phi R$ with $R$ being the $X(4160)$, $Y(3940)$, $Z(3930)$ and a predicted $J = 1$ resonances.

- Using the chiral unitary theory, these states are dynamically generated from the $V - V$ interaction, most notably the $D^* \bar{D}^*$ or $D_s^* \bar{D}_s^*$ states.

- We predict five ratios for the production of these $XYZ$ states. Some ratios only tell us that the resonance is built from $c \bar{c}$ or $b \bar{b}$ with or without extrahadronization.
In order to offer some extra test for the molecular composition of these states, we have evaluated the invariant mass distributions for the decays of $\bar{B}^0 \rightarrow K^* D^*\bar{D}^*$ and $\bar{B}_s^0 \rightarrow \phi D_s^*\bar{D}_s^*$ close to threshold and have made predictions for these magnitudes relative to the width for the production of the resonances.

The experimental investigation of these decay modes, and comparison with the predictions made, would shed light on the nature of these $XYZ$ states.

Thanks for your attention!