# The $Y(3940)$, $Z(3930)$ and the $X(4160)$ as dynamically generated resonances from the vector-vector interaction


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## Abstract


We study the vector-vector interaction within the framework of the hidden gauge formalism for the channels with quantum numbers Charm $C = 0$ and Strangeness $S = 0$ in the energy region around 4000 MeV. By looking for poles in the complex plane we find three resonances that could be identified by the mass, width and quantum numbers with the $Y(3940)$, $Z(3940)$ and $X(4160)$, these poles appear with isospin $I = 0$ and $J^{PC} = 0^{++}, 2^{++}$ and $2^{++}$ respectively. Whereas the $Y(3940)$ and $Z(3940)$ are coupled more strongly to $D^*\bar{D}^*$, the $X(4160)$ is basically a $D_s^*\bar{D}_s^*$ molecular state. Another two extra resonances appear in our approach with $I = 0, 1$ and $J^{PC} = 1^{+-}, 2^{++}$ which are not found in the PDG with masses $M = 3945, 3912$ MeV and widths $\Gamma = 0, 120$ MeV respectively.


## Introduction

The first of these XYZ states is the $X(3872)$ that was observed by the Belle Collaboration as a narrow peak near 3872 MeV in the $\pi^+\pi^-J/\psi$ invariant mass distributions in $B^- \to K^-\pi^+\pi^-J/\psi$ decays [1, 2]. The close value of the $X(3872)$ mass to the sum of the masses $m_{D^0}+m_{D^{*0}} = 3871.81 \pm 0.36$ MeV led to consider the $X(3872)$ as a molecule-like bound state of a $D^0$ and a $\bar{D}^{*0}$ meson, and much work on the properties of these possible systems has been done [4, 5, 6].

The next XYZ states, that we will consider in this paper, are the $X(3940)$, the $Y(3940)$, the $X(4160)$ and the $Z(3930)$. The $X(3940)$ was observed in the double-charmonium production reaction $e^+e^- \to J/\psi + X$ with mass $M = 3943 \pm 8$ MeV and width $\Gamma < 52$ MeV. After that Belle also observed a $D^*\bar{D}^*$ mass peak in the $e^+e^- \to J/\psi D^*\bar{D}^*$ reaction. Whereas the $X(3940) \to D\bar{D}^*$ has been observed, there is no signal for the $D\bar{D}$ or the $\omega J/\psi$ decays. Because of that and the fact that the $\eta_c(1S)$ and $\eta_c(2S)$ were also produced in double-charm production, it was believed that the $X(3940)$ could have $J^{PC} = 0^{-+}$, being a $3^1S_1$ charmonium state ($\eta_c''$), but there are problems with this assignment since in this case the $X(3940)$ should have a mass $\sim 4050$ MeV or even higher. Thus, it seems very unlikely that the $X(3940)$ is a $c\bar{c}$ state.

## Formalism

Our starting point is the Lagrangian, which involves the interaction of vector mesons amongst themselves, coming from the formalism of the hidden gauge symmetry (HGS) for vector mesons [7, 8, 9]

$$\mathcal{L}_{III} = -\frac{1}{4}\langle V_{\mu\nu}V^{\mu\nu}\rangle , \quad (1)$$

where the symbol $\langle\rangle$ stands for the trace in the $SU(4)$ space and $V_{\mu\nu}$ is given by

$$V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu - ig[V_\mu, V_\nu] , \quad (2)$$

with $g$ given by

$$g = \frac{M_V}{2f} , \quad (3)$$

and $f = 93$ MeV the pion decay constant. The vector field $V_\mu$ is represented by the $SU(4)$ matrix which is parametrized by 16 vector mesons including the 15-plet and singlet of $SU(4)$,

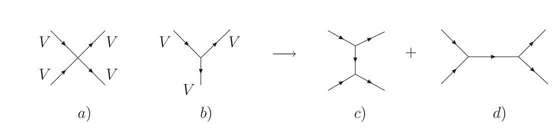
$$V_\mu = \begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & \rho^+ & K^{*+} & \bar{D}^{*0} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & K^{*0} & D^{*-} \\ K^{*-} & \bar{K}^{*0} & \phi & D_s^{*-} \\ D^{*0} & D^{*+} & D_s^{*+} & J/\psi \end{pmatrix}_\mu , \quad (4)$$

The interaction of $\mathcal{L}_{III}$ gives rise to a contact term

$$\mathcal{L}_{III}^{(c)} = \frac{g^2}{2}\langle V_\mu V_\nu V^\mu V^\nu - V_\nu V_\mu V^\mu V^\nu\rangle , \quad (5)$$

depicted in Fig. **??** a), and the three vector vertex

$$\mathcal{L}_{III}^{(3V)} = ig\langle(\partial_\mu V_\nu - \partial_\nu V_\mu)V^\mu V^\nu\rangle , \quad (6)$$



These amplitudes provide the kernel or potential $V$ to be used in the Bethe-Salpeter equation

$$T = (\hat{1} - VG)^{-1}V . \quad (7)$$

## Results

$$\sqrt{s}_{pole} = 3943 + i7.4,\ I^G[J^{PC}] = 0^+[0^{++}]$$

| $D^*\bar{D}^*$ | $D_s^*\bar{D}_s^*$ | $K^*\bar{K}^*$ | $\rho\rho$ | $\omega\omega$ |
|---|---|---|---|---|
| $18810 - i682$ | $8426 + i1933$ | $10 - i11$ | $-22 + i47$ | $1348 + i234$ |

| $\phi\phi$ | $J/\psi J/\psi$ | $\omega J/\psi$ | $\phi J/\psi$ | $\omega\phi$ |
|---|---|---|---|---|
| $-1000 - i150$ | $417 + i64$ | $-1429 - i216$ | $889 + i196$ | $-215 - i107$ |

Table 1. Couplings $g_i$ in units of MeV for $I = 0$, $J = 0$.

$$\sqrt{s}_{pole} = 3922 + i26,\ I^G[J^{PC}] = 0^+[2^{++}]$$

| $D^*\bar{D}^*$ | $D_s^*\bar{D}_s^*$ | $K^*\bar{K}^*$ | $\rho\rho$ | $\omega\omega$ |
|---|---|---|---|---|
| $21100 - i1802$ | $1633 + i6797$ | $42 + i14$ | $-75 + i37$ | $1558 + i1821$ |

| $\phi\phi$ | $J/\psi J/\psi$ | $\omega J/\psi$ | $\phi J/\psi$ | $\omega\phi$ |
|---|---|---|---|---|
| $-904 - i1783$ | $1783 + i197$ | $-2558 - i2289$ | $918 + i2921$ | $91 - i784$ |

Table 2. Couplings $g_i$ in units of MeV for $I = 0$, $J = 2$.

$$\sqrt{s}_{pole} = 3945 + i0,\ I^G[J^{PC}] = 0^-[1^{+-}]$$

| $D^*\bar{D}^*$ | $D_s^*\bar{D}_s^*$ | $K^*\bar{K}^*$ |
|---|---|---|
| $18489 - i0.78$ | $8763 + i2$ | $11 - i38$ |

Table 3.Couplings $g_i$ in units of MeV for $I = 0$, $J = 1$.

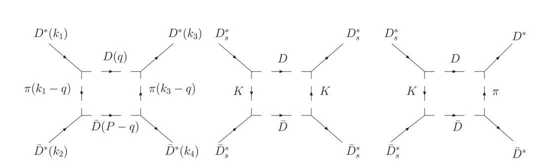


FIGURE 1: $D\bar{D}$-box diagrams for the $D^*\bar{D}^*$ and $D_s^*\bar{D}_s^*$ channels.

Taking the coupling $g_{Y\omega J/\psi} = (-1429 - i\,216)$ MeV from Table 1

$$\Gamma((3943, 0^+[0^{++}]) \to \omega J/\psi) = \frac{p\,|g_{Y\omega J/\psi}|^2}{8\pi M_Y^2} \quad (8)$$

we obtain $\Gamma((3943, 0^+[0^{++}]) \to \omega J/\psi) = 1.52$ MeV, which is compatible with $\Gamma(Y(3940) \to \omega J/\psi) > 1$ MeV, obtained from the measured product of branching fractions $\mathcal{B}(B \to KY(3940))\mathcal{B}(Y(3940) \to \omega J/\psi)$ ($(7.1 \pm 3.4) \times 10^{-5}$, reported by Belle, and $(4.9 \pm 1.1) \times 10^{-5}$ according to Babar).

| $I^G[J^{PC}]$ | Theory | | Experiment | | | |
|---|---|---|---|---|---|---|
| | Mass [MeV] | Width [MeV] | Name | Mass [MeV] | Width [MeV] | $J^{PC}$ |
| $0^+[0^{++}]$ | 3943 | 17 | $Y(3940)$ | $3943 \pm 17$ | $87 \pm 34$ | $J^{P+}$ |
| | | | | $3914.3^{+4.1}_{-3.8}$ | $33^{+12}_{-8}$ | |
| $0^-[1^{+-}]$ | 3945 | 0 | "$Y_p(3945)$" | | | |
| $0^+[2^{++}]$ | 3922 | 55 | $Z(3930)$ | $3929 \pm 5$ | $29 \pm 10$ | $2^{++}$ |
| $0^+[2^{++}]$ | 4157 | 102 | $X(4160)$ | $4156 \pm 29$ | $139^{+113}_{-65}$ | $J^{P+}$ |
| $1^-[2^{++}]$ | 3912 | 120 | "$Y_p(3912)$" | | | |

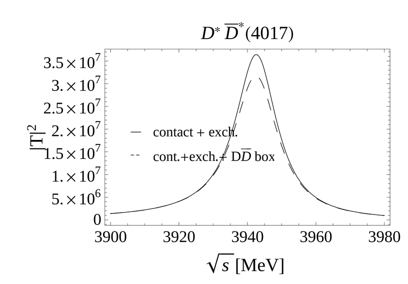


FIGURE 2: $|T|^2$ for $I = 0$ and $J = 0$ before and after the inclusion of the $D\bar{D}$ box diagrams.

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