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# Evidence that the $Y(4660)$ is an $f_0(980)\psi'$ bound state

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ABSTRACT

We demonstrate that the experimental information currently available for the $Y(4660)$ is consistent with its being an $f_0(980)\psi'$ molecule. Possible experimental tests of our hypothesis are presented.



**1.** In recent years a large number of new hidden and open charm states were discovered experimentally above the first inelastic thresholds. For most of them the masses have in common that they deviate significantly from the predictions of the quark model [1]—which on the other hand works very well below the thresholds—and are positioned very close to an $s$-channel threshold [2]. For recent reviews see, e.g., Ref. [3].

The proximity of the thresholds initiated a lot of theoretical studies, in order to reveal a possible molecular structure of those states. E.g., in Ref. [4] the $D_s(2317)$, located just below the $KD$-threshold, was studied within the molecular model and the $X(3872)$, located right at the $\bar{D}D^*$ threshold, was investigated in Ref. [5]. However, so far no consensus exists on the true nature of those states and, e.g., four-quark interpretations [6] and even conventional $\bar{q}q$ states are still under discussion [7].

In Ref. [8] it was argued that there is a way to model independently identify hadronic molecules in the spectrum. The method is based on a time-honored analysis by Weinberg [9] and applies, if the pole is very close to the threshold of the constituent particles that form the bound state in an $s$-wave. The method relates the effective coupling constant of the bound state to its constituents, $g$, directly to the molecular admixture of the state. Especially, one may write for a pure molecule

$$\frac{g^2}{4\pi} = \frac{(m_1+m_2)^{5/2}}{(m_1 m_2)^{1/2}}\sqrt{32\epsilon}, \qquad (1)$$

where $m_1$ and $m_2$ denote the masses of the constituents and $\epsilon$ the binding energy.

In this Letter we discuss the nature of the $Y(4660)$ as a candidate for an $f_0(980)\psi'$ bound state. So far the $Y(4660)$ was seen only in the $\pi^+\pi^-\psi'$ invariant mass distribution in $e^+e^- \to \gamma_{ISR}\pi^+\pi^-\psi'$ with a mass of $4664 \pm 11 \pm 5$ MeV and a width of $48 \pm 15 \pm 3$ MeV [10]. Such a structure was neither observed in $e^+e^- \to \gamma_{ISR}\pi^+\pi^- J/\psi$ [11], nor in the exclusive $e^+e^- \to D\bar{D}, D\bar{D}^*, D^*\bar{D}^*, D\bar{D}\pi$ cross sections [12], nor in the process $e^+e^- \to J/\psi D^{(*)}\bar{D}^{(*)}$ [13]. These facts would severely challenge any attempt explaining the state as a canonical $c\bar{c}$ charmonium, e.g. $5^3S_1$ as in Ref. [14]. The $Y(4660)$ is suggested to be a baryonium state in Ref. [15]. The difficulties in the canonical charmonium interpretation could be explained naturally, if the $Y(4660)$ were an $f_0(980)\psi'$ bound state, because it would decay dominantly via the decay of the $f_0(980)$, i.e. $Y(4660) \to \psi' f_0(980) \to \psi'[\pi\pi]$ and $Y(4660) \to \psi' f_0(980) \to \psi'[K\bar{K}]$. The nominal threshold of the $f_0(980)$–$\psi'$ system is at $4666 \pm 10$ MeV if we take the PDG value of the $f_0(980)$ mass [16]. Note that the interaction between a heavy quarkonium and a light hadron is expected to be dominated by the QCD van der Waals interaction which is attractive [17].

In the $\pi\pi$ invariant mass a clear $f_0(980)$ peak is visible. Clearly, if the $Y(4660)$ were a conventional $f_0\psi'$ bound state, it could not decay to this channel. This is possible only because of the finite width of the $f_0(980)$, mainly due to its decay to the $\pi\pi$ channel. We will perform our analysis based on the following reasoning: if the $f_0$ were a stable particle, also the $Y(4660)$ were stable. Then we could calculate the effective coupling constant of $Y$ to $\psi' f_0$ using Eq. (1). The central assumption is that this coupling constant does not change as the two pion channel is switched on—a similar ansatz leads to a successful phenomenology for the $f_0(980)$ treated as a $\bar{K}K$ molecule [18]. Under this assumption we can predict not only the prominent component of the width of the $Y(4660)$ but also its spectral shape using the mass and the over all normalization as the only input. As additional non-trivial result

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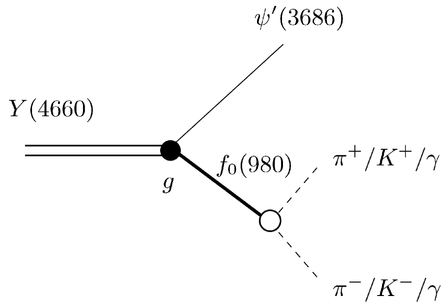


**Fig. 1.** Diagram illustrating the most prominent decay channels of the $Y(4660)$ in the molecular model. The solid black dot denotes the $Yf_0\psi'$ vertex, whose strength parameter $g$ is fixed within the molecular model through Eq. (1). The decay vertices for $f_0$, shown as open circle, are fixed from other data.

we can also predict the strength and the shape of the decay to $\bar{K}K$ and $\gamma\gamma$. The possible decay chains are illustrated in Fig. 1. As we will see, the resulting spectra are in excellent agreement with the existing data. We interpret this as a strong support in favor of a molecular interpretation for the $Y(4660)$.

**2.** The $Y(4660)$ was observed as a structure in the $\psi'\pi\pi$ invariant mass distribution. In addition, in Ref. [10], also the $\pi\pi$ invariant mass distribution is presented, which was found after applying an appropriate cut to the $\psi'\pi\pi$ invariant mass. Both distributions can be derived from the same differential rate, under the assumption that the pion pair stems from the decay of an $f_0$. One gets

$$\frac{d^2\mathcal{W}(e^+e^-\to\psi'\pi^+\pi^-)}{dM^2\,dm_{\pi\pi}^2}=N\left|G_Y(M)\right|^2\frac{d\Gamma_Y^{[\pi^+\pi^-]}}{dm_{\pi\pi}^2},\tag{2}$$

where $G_Y(M)$ denotes the physical $Y$-propagator, to be specified below and $N$ is a normalization constant, which contains, besides the electron–photon vertex and the photon propagator, both indeed constant to very high accuracy in the range of $M$ of relevance here, also the detector acceptance. The decay $Y\to\psi'\pi^+\pi^-$ is described by

$$\frac{d\Gamma_Y^{[\pi^+\pi^-]}}{dm_{\pi\pi}^2}=\frac{g^2}{8\pi}\theta(M-M_{\psi'\pi\pi})\frac{p}{M^2}\rho_{f_0}^{[\pi^+\pi^-]}.\tag{3}$$

Here $p$ denotes the c.m.s. momentum of the $\psi'$ for given values of the $\pi\pi$ invariant mass, $m_{\pi\pi}$, and the $\psi'\pi\pi$ invariant mass, $M$, and $M_{\psi'\pi\pi}=m_{\pi\pi}+M_{\psi'}$. The effective coupling constant $g$ is not a free parameter, but can be determined for any given value of the mass of the $Y$ from Eq. (1). The quantity $\rho_{f_0}^{[\pi^+\pi^-]}(m_{\pi\pi})$ denotes the $\pi^+\pi^-$ fraction of the $f_0$ spectral function. It is normalized according to

$$\int dm_{\pi\pi}^2\,\rho_{f_0}^{[\pi^+\pi^-]}(m_{\pi\pi})=\Gamma_{f_0}^{[\pi^+\pi^-]}/\Gamma_{f_0}^{\rm tot}.$$

With this normalization Eq. (3) goes to the standard expression for a two particle decay in the stable particle limit for the $f_0$.

A high quality data set for the $f_0$ was collected recently by KLOE [19] based on the reaction $\phi\to\gamma\pi\pi$. The data was analyzed using the so-called kaon loop model [20] and provided parameters for the $f_0$ with very little uncertainty. To be concrete, we use

$$\rho_{f_0}^{[\pi^+\pi^-]}(m)=\frac{1}{\pi}\frac{{\rm Im}(\Pi_{f_0}^{\pi^+\pi^-}(m))}{|m^2-m_{f_0}^2+\sum_{ab}\hat{\Pi}_{f_0}^{ab}(m)|^2},\tag{4}$$

where the $\hat{\Pi}_{f_0}^{ab}(m)=\Pi_{f_0}^{ab}(m)-{\rm Re}(\Pi_{f_0}^{ab}(m_{f_0}))$ denote the renormalized self-energies of the $f_0$ with respect to the channel $ab$. Analytic expressions are given in Ref. [20].[1] The input parameters are taken from the fits provided in Ref. [19]. To be concrete, for all the curves shown below we used the central values of the various parameters of fit $K2$ shown in Table 4 of that reference, thus we used $m_{f_0}=0.9862$ GeV, $g_{f_0K^+K^-}=3.87$ GeV, and $g_{f_0\pi^+\pi^-}=-2.03$ GeV, while the couplings for the neutral channels were fixed using the isospin relations. We checked that the other parameter sets give very similar results to the ones discussed in detail below.

The only missing piece is the physical $Y$ propagator. In Eq. (3) an explicit expression is given for the partial width to $\psi'\pi^+\pi^-$. However, in order to derive the physical propagator, all relevant decay channels need to be included. Within our model we assume that the $Y$ decays predominantly through the $f_0$, thus a consistent treatment requires that all decay channels of the $f_0$ also contribute to the width of the $Y$ and thus to the propagator. It is straightforward to extend Eq. (3) also to the $\pi^0\pi^0$ channel as well as to the kaon channels without any additional free parameters—also for these channels we use the results of the fit to the KLOE data presented in Ref. [19]. Thus we get for the total width of the $Y$ at a given value of $M$, under the assumption that it is saturated by the $\psi'f_0$ decay

$$\Gamma_Y^{\rm tot}(M^2)=\sum_{ab}\theta\big(M-M_{\psi'}-\sqrt{s_{\rm thr}^{ab}}\big)\times\int_{s_{\rm thr}^{ab}}^{(M-M_{\psi'})^2}dm_{ab}^2\frac{d\Gamma_Y^{[ab]}(M,m_{ab})}{dm_{ab}^2},\tag{5}$$

where $s_{\rm thr}^{ab}=(m_a+m_b)^2$. In order to get a $Y$ propagator with the correct analytical properties we need to continue the contribution from the $\bar{K}K\psi'$ channel also to below its threshold. For this we use a dispersion integral, which gives us an expression for the $Y$ self-energy, $\Pi_Y(M)$, for arbitrary values of $M$

$$\Pi_Y(M)=\frac{1}{\pi}\int_{M_{\rm thr}^2}^{\infty}ds\frac{M_Y\Gamma_Y^{\rm tot}(s)}{s-M^2-i\epsilon},\tag{6}$$

where $M_{\rm thr}=M_{\psi'}+2m_\pi$ denotes the lowest physical threshold of relevance here. Note, this treatment is completely consistent to what was done for the $f_0$—one way to derive the self-energies $\Pi_{f_0}^{ab}(m)$ given above is through a dispersion integral with the two-body phase space as input. With the self-energies at hand we may now give the expression for the physical propagator of the $Y(4660)$

$$G_Y(M)=\frac{1}{M^2-M_Y^2+\hat{\Pi}_Y(M)},\tag{7}$$

where, as above, we defined $\hat{\Pi}_Y(M)=\Pi_Y(M)-{\rm Re}(\Pi_Y(M_Y))$.

**3.** Our model has only 2 free parameters, namely, the mass of the $Y$, $M_Y$, and the normalization constant, $N$, introduced in Eq. (2). We now proceed as follows: the count rate, $R$, in the $\psi'\pi^+\pi^-$ invariant mass spectrum is given by

$$R(M)=\int_{4m_\pi^2}^{M-M_{\psi'}}dm_{\pi\pi}^2\frac{d^2\mathcal{W}(e^+e^-\to\psi'\pi^+\pi^-)}{dM^2\,dm_{\pi\pi}^2},\tag{8}$$

using the expression for the differential rate $\mathcal{W}$ of Eq. (2). The range of parameters allowed by the data is then determined from

[1] We only include the $\pi\pi$ and the $\bar{K}K$ channels, for the others give a negligible contribution.

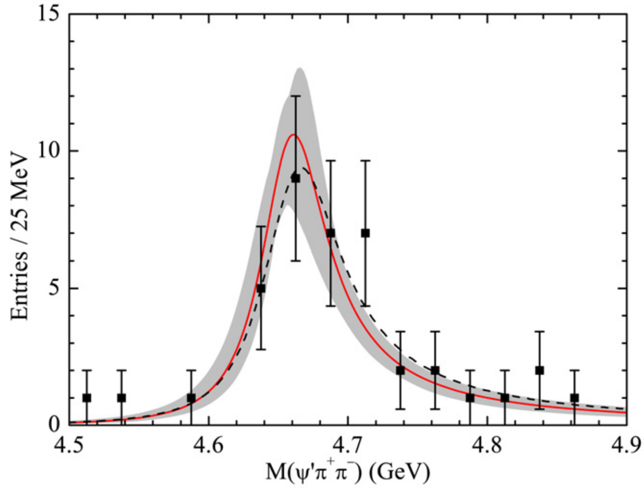


**Fig. 2.** Comparison of the line shape in the $\psi'\pi^+\pi^-$ invariant mass distribution derived from the molecular model with the data. The solid line shows the result of our best fit, while the shaded area shows the uncertainty that emerges from the fit. The dashed line shows the best fit result, if also the effective coupling is part of the fit, as discussed in the final section.

a fit to the experimental data for the $\psi'\pi^+\pi^-$ spectrum—we remind the reader that the coupling constant $g$ is fixed from Eq. (1) for any given value of $M_Y$. We find

$$N = 10 \pm 2\ \text{GeV}^3, \qquad M_Y = 4665^{+3}_{-5}\ \text{MeV}. \tag{9}$$

This range of mass values corresponds to a range of $g = 11, \ldots, 14$ GeV for the effective coupling constant. The best fit is shown as the solid line in Fig. 2—the uncertainty that emerges from the fit is reflected by the grey band. For the best fit $\chi^2/\text{d.o.f.} = 0.5$. The first observation is that the resulting invariant mass distribution visibly deviates from a standard Breit–Wigner shape. This is a direct consequence of our starting assumption, namely that the $Y(4660)$ is predominantly composed of an $f_0$ and a $\psi'$, not only since the mass of the $Y$ is very close to the nominal $f_0\psi'$ threshold, but also because of the proximity of the kaon channels, which are very important for the structure of the $f_0$.

Since now all parameters of our model are fixed we can predict other channels. Recently high quality data was measured for $f_0 \to \gamma\gamma$ [21]. Within our approach we thus predict that the shape in the $\psi'\gamma\gamma$ invariant mass is identical to that measured for $\psi'\pi^+\pi^-$, however, down scaled by the relevant ratio of branching ratios. In addition we can also predict the signals for the spectra of $\pi\pi$ and $K\bar{K}$ as they emerge from the decay of the $Y$. The predicted rate, $R_{ab}(m_{ab})$, again follows directly from Eq. (2)

$$R_{ab}(m_{ab}) = \int_{(4.5\ \text{GeV})^2}^{(4.9\ \text{GeV})^2} dM^2 \frac{d^2\mathcal{W}(e^+e^- \to \psi' ab)}{dM^2\, dm_{ab}^2}, \tag{10}$$

where the limits of integration are chosen identical to the cuts used to get the experimental rate [10]. The corresponding results are shown in Fig. 3. If a signal of the given shape and strength were found in the $\psi'\bar{K}K$ invariant mass distribution, it would provide a strong support for the assumed prominent role of $f_0\psi'$ for the structure of the $Y$.

**4.** To summarize, we calculated the invariant mass spectrum for $\psi'\pi^+\pi^-$ as well as the corresponding $\pi\pi$ and $\bar{K}K$ spectra in the mass range of the $Y(4660)$ under the assumption that the $Y(4660)$ is an $f_0(980)\psi'$ bound state and $f_0(980)\psi'$ is its only decay channel of relevance. A very good description of both spectra, where data exist, was achieved. Especially, we find a visible deviation from a Breit–Wigner shape for the $\psi'\pi\pi$ spectrum, consistent

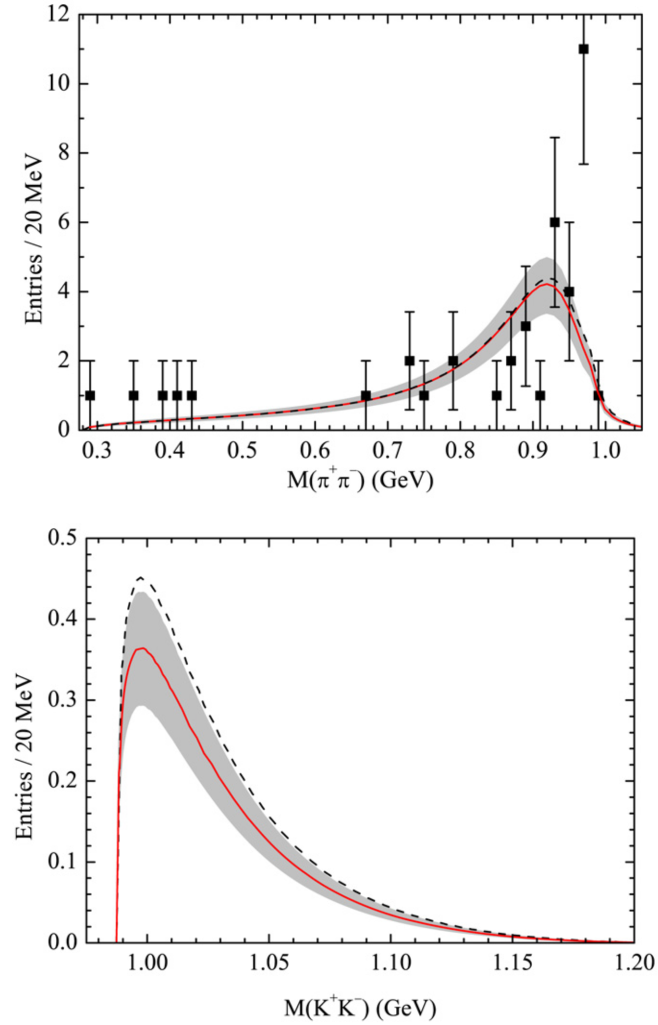


**Fig. 3.** Predictions for the $\pi\pi$ and $\bar{K}K$ invariant mass distributions.

with the data, although data with better statistics would be very welcome to strengthen this point.

In principle our method also allows one to estimate the possible contribution of channels other than $f_0\psi'$ to the width of the $Y(4660)$. One just needs to add the term $iM_Y\Gamma_{\text{add}}$ to the denominator of $G_Y(M)$, defined in Eq. (7) and repeat the fitting procedure. With this we get $\Gamma_{\text{add}} = (30 \pm 30)$ MeV—thus, before better data is available no reliable bound for the possible additional width can be deduced. However, it is important to observe that the value extracted from the current data is consistent with zero within the uncertainty.

We also checked what happens, if we do not fix the effective coupling $g$ according to Eq. (1), but allow it to float as well. Then we find $M_Y = (4672 \pm 9)$ MeV and $g = (13 \pm 2)$ GeV with $\chi^2/\text{d.o.f.} = 0.4$. The result of the best fit is shown as the dashed line in Figs. 2 and 3. Thus the effective coupling constant extracted from this three parameter agrees to that found before, only that the three parameter fit prefers a larger value of the mass, partially inconsistent with a molecular picture—for masses at the higher end the mass of the $Y$ is even larger than $M_{\psi'} + m_{f_0}$. Also here we need to conclude that more data are needed to draw a more firm conclusion—especially we showed that the $\bar{K}K$ invariant mass distribution is quite sensitive to the mass of the $Y(4660)$—cf. lower panel of Fig. 3. It is in any case important to stress that the fit calls for a large coupling constant for $Y \to f_0\psi'$, which is naturally explained by the assumption that the $Y(4660)$ is generated dynamically in the $f_0\psi'$ channel.

We take our results as a strong evidence for a molecular interpretation of the $Y(4660)$. We stress that a measurement of the $\psi'\bar{K}K$ channels as well as an improvement of the resolution of the existing data would allow for non-trivial tests of our hypothesis.

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