

Interpretation of $D(2637)$ from heavy quark symmetry

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(Received 5 January 1999; published 9 August 1999)

We demonstrate from heavy quark symmetry that the width of $D(2637)$ claimed by the DELPHI Collaboration is inconsistent with any bound state with one charm quark predicted in the $D(2637)$ mass region, except possibly D_3^* , $D_{2j_q=5/2}$ or D' . The former two possibilities are favored by heavy quark mass relations. [S0556-2821(99)06117-2]

PACS number(s): 14.40.Lb, 13.25.Es, 13.25.Ft, 14.40.Ev

The DELPHI Collaboration recently presented evidence for a new state $D(2637)$ at $2637 \pm 2 \pm 6$ MeV with a width of < 15 MeV at 95% confidence [1]. A signal of 66 ± 14 events was detected, a 4.7σ effect. The state was observed decaying to $D^{*+} \pi^+ \pi^-$. However, its existence has not been confirmed by the CLEO and OPAL Collaborations in the same decay channel [2]. Moreover, there is no evidence for $D(2637)$ in $D^* \pi$ [1,2].

In this Brief Report we shall assume the validity of the DELPHI claim, and provide theoretical interpretations for $D(2637)$, based on two assumptions:

(1) The validity of lowest order heavy quark symmetry decay relations between the K -meson and corresponding D -meson systems.

(2) The validity of experimental data on the established K -mesons $K^*(1410)$, $K^*(1680)$, $K_0^*(1430)$, $K_1(1400)$ and $K_3^*(1780)$ [3].

These are the *only* assumptions that will be made, unless otherwise indicated. The latter assumption is inevitable given that no new data is likely to be forthcoming soon. The former assumption is needed to make extrapolations, independent of detailed dynamical models, from known K -meson decays to unknown D -meson decays. Although not always good within the simplest form factor assumptions (see below), it has been argued to be qualitatively valid [4] in an analysis of $K_1(1270)$ and $K_2^*(1430)$ [5,6]. A specific example of how heavy quark symmetry for strange quarks gives predictions in the right ballpark is as follows. The D-to S-wave width ratio for $K_1(1400) \rightarrow K^* \pi$ is 0.04 ± 0.01 [3] (heavy quark symmetry predicts zero [4]); and for $K_1(1270) \rightarrow K^* \pi$ is 1.0 ± 0.7 [3] (heavy quark symmetry predicts infinity [4]).

The radial excitation of the D^* , referred to as $D^{*'}$, is predicted to have a mass of 2640 MeV in a model which predicted the $D_2^*(2460)$ mass within 40 MeV of experiment [7]; and 2629 MeV in a recent model which is in agreement within 20 MeV for the observed charm orbital states [8]. The noticeable proximity of these potential model predictions to the mass of $D(2637)$ leads DELPHI to identify it as $D^{*'}$, and hence as $J^P = 1^-$. However, there are several experimentally unobserved conventional mesons which can also decay to $D^* \pi \pi$ and are expected in potential models in the vicinity

of $D(2637)$. Of these, the radially excited D with $J^P = 0^-$, referred to as D' , would be nearest in mass at 2580 MeV [7] or 2579 MeV [8]. Next nearest would be the $D_{1j_q=1/2}^*$, a possibly observed [9] 1^+ at 2460 MeV [7], 2501 MeV [8] or 2585 MeV [10]; and the 0^+ D_0^* at 2400 MeV [7], 2438 MeV [8] or 2554 MeV [10]. The 1^- $D_{1j_q=3/2}$ is at 2820 MeV [7]. The 3^- D_3^* should be at 2830 MeV [7] or 2760 ± 70 MeV [11]. The 2^- states $D_{2j_q=5/2}$ and $D_{2j_q=3/2}$ are within 20 MeV of D_3^* [7]. Given the small error bars of the DELPHI mass measurement, all interpretations except $D^{*'}$ fail on mass grounds.

The purpose of this Brief Report is to check which of the preceding possibilities can reproduce the tiny total width of < 15 MeV claimed by DELPHI, assuming them to have the mass of $D(2637)$. The masses of all experimentally known states will be taken from the Particle Data Group [3].

For a given heavy-light meson with total angular momentum \vec{J} , let \vec{s}_Q ($s_Q = \frac{1}{2}$) be the spin of the heavy quark and \vec{j}_q the total angular momentum of the light degrees of freedom. Consider the decay of a heavy-light meson characterized by J, j_q to an outgoing heavy-light meson characterized by J', j'_q and a light meson with spin s_h . The light meson has orbital angular momentum l relative to the outgoing heavy-light meson. The decay amplitude satisfies certain symmetry relations because the decay dynamics become independent of the heavy quark spin in the heavy quark limit of QCD [12]. The two-body decay width can be factored into a reduced form factor multiplied by a normalized 6- j symbol [12]

$$\Gamma = \left(\sqrt{(2J'+1)(2j_q+1)} \begin{Bmatrix} s_Q & j'_q & J' \\ j_h & J & j_q \end{Bmatrix} \right)^2 \times p^{2l+1} F_{j_h}^{j_q j'_q}(p^2) \quad (1)$$

where $\vec{j}_h \equiv \vec{s}_h + \vec{l}$. Here p is the magnitude of the three-momentum of the decay products in the rest frame of the initial state. Equation (1) neglects corrections to the heavy quark limit, except in as far as they modify p . One essential idea of the heavy quark limit is that the spin of the heavy quark and the total angular momentum of the light degrees of freedom are separately conserved [12], i.e. $\vec{j}_q = \vec{j}'_q + \vec{j}_h$. This conservation law is in addition to the usual conditions of conservation of total angular momentum $\vec{J} = \vec{J}' + \vec{j}_h$ and par-

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TABLE I. Widths of $D(2637)$ to $D\pi$ and $D^*\pi$ in MeV. The interpretation and j_q of $D(2637)$ is given in the first and third columns respectively. Blank entries are identical to those above them. Since there are reasons to doubt that $K^*(1410)$ is the radially excited K^* , the $K^*(1680)$ is often taken to be the radial excitation [3]. Another quark model interpretation of $K^*(1680)$ is as a D-wave meson [3], so that $j_q = \frac{3}{2}$. The only interpretation of $K_0^*(1430)$ is as a P-wave meson [3], so that $j_q = \frac{1}{2}$.

$D(2637)$	K-meson data used [16]	j_q	Form factor	$D\pi$	$D^*\pi$
$D^{*'}_0$	$\Gamma(K^*(1410) \rightarrow K\pi) = 15$ MeV	$\frac{1}{2}$	$F_1^{1/2} 1^{1/2}(0)$	17	22
	$\Gamma(K^*(1680) \rightarrow K\pi) = 125$ MeV			86	115
	$\Gamma(K^*(1680) \rightarrow K^*\pi) = 96.3$ MeV			53	71
D'	$\Gamma(K^*(1410) \rightarrow K\pi)$			-	33
	$\Gamma(K^*(1680) \rightarrow K\pi)$			-	172
	$\Gamma(K^*(1680) \rightarrow K^*\pi)$			-	106
D_0^*	$\Gamma(K_0^*(1430) \rightarrow K\pi) = 270$ MeV		$F_0^{1/2} 1^{1/2}(0)$	270	-
$D_{1j_q=1/2}^*$				-	260
$D_{1j_q=3/2}$	$\Gamma(K^*(1680) \rightarrow K\pi)$	$\frac{3}{2}$	$F_1^{3/2} 1^{1/2}(0)$	87	29
	$\Gamma(K^*(1680) \rightarrow K^*\pi)$			213	71
$D_{2j_q=3/2}$	$\Gamma(K^*(1680) \rightarrow K\pi)$			-	86
	$\Gamma(K^*(1680) \rightarrow K^*\pi)$			-	212

ity. For the remainder of this Brief Report we shall restrict to l allowed by all these conservation conditions. Heavy quark symmetry does not predict the magnitude and functional dependence of the reduced form factor $F_{j_h l}^{j_q j'_q}(p^2)$ for a particular decay. Once determined from experimentally well established decays of K -mesons with given j_q, j'_q , this quantity may be used to predict related decays of both K - and D -mesons with the same j_q, j'_q .

We shall assume a Gaussian form for the reduced form factor [5]

$$F_{j_h l}^{j_q j'_q}(p^2) = F_{j_h l}^{j_q j'_q}(0) \exp(-p^2/6\beta^2). \quad (2)$$

TABLE II. Partial widths of D_3^* and $D_{2j_q=5/2}$ in MeV. Blank entries are identical to those above them. In some form factors we have explicitly indicated the light meson η or ρ , in order to distinguish them from form factors for π . The only quark model interpretation of $K_3^*(1780)$ is as a D-wave meson [3], so that $j_q = \frac{5}{2}$. Decays of $D(2637)$ to $D\omega, D^*\rho$ are below threshold by more than half a width of ω and ρ respectively, and are not calculated in this Brief Report. However, $D_{2j_q=5/2} \rightarrow D\omega$ and $D_3^*, D_{2j_q=5/2} \rightarrow D^*\rho$ can be in P-wave and hence competitive with the rates in the text, although current experimental data on K-mesons do not give sufficient information to estimate these rates from heavy quark symmetry. $D_{2j_q=5/2} \rightarrow D_0^*\pi$ is a D-wave decay and $D_3^*, D_{2j_q=5/2} \rightarrow D_{1j_q=1/2}^*\pi$ a D-wave decay at threshold, using the $D_{1j_q=1/2}^*$ and D_0^* masses of Ref. [8]. These decays cannot be estimated from experimental data. (†) Assuming SU(3) symmetry. (‡) This is an F-wave decay at threshold, and hence very sensitive to phase space. We smear the partial width [Eqs. (1) and (2)] over a relativistic Breit-Wigner form to take account of the 150 MeV width of the ρ . (♣) This decay involves form factors which cannot be estimated from experimental data. (II) The width of $D_2^*(2460)$ has been smeared over.

K-meson data used [16]	Form factor	Decay mode	D_3^*	$D_{2j_q=5/2}$
$\Gamma(K_3^*(1780) \rightarrow K\pi) = 29.9$ MeV	$F_3^{5/2} 3^{1/2}(0)$	$D\pi$	7.8	-
		$D^*\pi$	3.4	5.9
$\Gamma(K_3^*(1780) \rightarrow K^*\pi) = 32$ MeV		$D\pi$	22	-
		$D^*\pi$	7.8	17
$\Gamma(K_3^*(1780) \rightarrow K\pi, K^*\pi)$		$D_s K \dagger$	<.6	-
		$D_s^* K \dagger$	~0	~0
$\Gamma(K_3^*(1780) \rightarrow K\eta) = 48$ MeV	$F_3^{5/2} 3^{1/2} \eta(0)$	$D\eta$	2.9	-
		$D^*\eta$	0.1	0.2
$\Gamma(K_3^*(1780) \rightarrow K\rho) = 49$ MeV	$F_3^{5/2} 3^{1/2} \rho(0)$	$D\rho \ddagger$	0.7	♣
$\Gamma(K_3^*(1780) \rightarrow K_2^*(1430)\pi) < 25$ MeV	$F_2^{5/2} 2^{3/2}(0)$	$D_2^*(2460)\pi$ II	<0.5	<0.2
		$D_1(2420)\pi$	<0.2	<1.1

radially excited K^* [3], so that $j_q = \frac{1}{2}$. However, $K^*(1410)$ may have a non-conventional-meson component, e.g. a low-lying 1^- hybrid meson with $j_q = \frac{1}{2}$. Noting that the π has $s_h = 0$, we deduce from Eqs. (1) and (2), using the experimental data on $\Gamma(K^*(1410) \rightarrow K\pi)$, the value of $F_{1\frac{1}{2}1\frac{1}{2}}^{1/2}(0)$. From this $\Gamma(D^{*'} \rightarrow D\pi, D^*\pi)$ is calculated. The total width of $D^{*'}$ is found to be appreciably higher than the DELPHI value. The same holds true for all other possibilities explored in Table I.

$K_3^*(1780)$ has been used in an analogous study to the one in this Report [5,6]. There the heavy quark symmetry partners D_3^* and $D_{2j_q=5/2}$ have been found to be 193 MeV and 99 MeV wide [6], respectively, due to the high mass of 2830 MeV used [15]. In this work we use the mass of the $D(2637)$ by fiat, so that the total widths should be substantially smaller.

The partial widths of D_3^* are estimated in Table II. All decay modes other than $D\pi$ and $D^*\pi$ contributes 4–5 MeV. The $D\pi$ and $D^*\pi$ partial widths depend on which K-meson decay they are fixed to. Fixing from $K_3^*(1780) \rightarrow K\pi$, a partial width with a small experimental uncertainty [16], yields a total D_3^* width of 15–16 MeV. Fixing from $K_3^*(1780) \rightarrow K^*\pi$ has the advantage that the dominant decay $D_3^* \rightarrow D\pi$ has almost exactly the same momentum p , so that $\Gamma(D_3^* \rightarrow D\pi)/\Gamma(K_3^*(1780) \rightarrow K^*\pi) = 3/4$ from heavy quark symmetry independent of the assumed form factor. Here the total D_3^* width is 36–37 MeV. Since we have not estimated $D_3^* \rightarrow D^*(\pi\pi)_S$ due to lack of experimental data from K-mesons it appears likely that D_3^* cannot be interpreted as $D(2637)$ based on its total width, although the possibility cannot be eliminated.

The decays of $D_{2j_q=5/2}$ are also estimated in Table II. The total estimated width of $D_{2j_q=5/2}$ is 6–7 or 17–18 MeV depending on whether we fix respectively from $K_3^*(1780) \rightarrow K\pi$ or $K_3^*(1780) \rightarrow K^*\pi$. Since we cannot estimate $D_{2j_q=5/2} \rightarrow D(\pi\pi)_S$, $D^*(\pi\pi)_S$, which have substantial phase space, the balance of probability is that the total $D_{2j_q=5/2}$ width is not consistent with the DELPHI value.

The conclusion here is that all interpretations of $D(2637)$ have too large total widths, except possibly D_3^* and $D_{2j_q=5/2}$, of which $D_{2j_q=5/2}$ appears to be the narrowest candidate.

Based on the 3P_0 model decay amplitude, we postulate the nodal Gaussian form factor [14]

$$F_{j_h l}^{j_q j'_q}(p^2) = F_{j_h l}^{j_q j'_q}(0) \left(1 - \frac{2}{15} \frac{p^2}{\tilde{\beta}^2} \right)^2 \exp\left(-\frac{p^2}{6\tilde{\beta}^2} \right) \quad (3)$$

at the cost of introducing an extra parameter $\tilde{\beta}$. The experimental motivation for this form factor is that the experimental ratio $\Gamma(K^*(1410) \rightarrow K\pi)/\Gamma(K^*(1410) \rightarrow K^*\pi) < 0.16$ [3] is at least a factor of eight smaller than the heavy quark symmetry prediction with a Gaussian form factor. This indicates the need for a form factor which can additionally suppress $K^*(1410) \rightarrow K\pi$. The theoretical motivation is that the radially excited $K^*(1410)$ should have a node in its wave

function, which would naturally translate into a node in the decay amplitude. A nodal Gaussian form factor [Eq. (3)] is accordingly found in the phenomenologically successful 3P_0 model; for the decay to $D\pi$, $D^*\pi$ of all interpretations of $D(2637)$ discussed in the previous section, except D_3^* and $D_{2j_q=5/2}$. For these interpretations we perform a search for decays to $D\pi$ and $D^*\pi$ consistent with the DELPHI bound, using the previous methods. Only successful searches are highlighted.

D' , using $K'(1410)$. Using Eqs. (1) and (3), the ratio $\Gamma(K^*(1410) \rightarrow K\pi)/\Gamma(K^*(1410) \rightarrow K^*\pi)$ and width $\Gamma(K^*(1410) \rightarrow K\pi)$ from experiment [3,16], we determine $F_{1\frac{1}{2}1\frac{1}{2}}^{1/2}(0)$ and $0.21 \leq \tilde{\beta} \leq 0.25$ GeV. From Eqs. (1) and (3) we estimate $\Gamma(D' \rightarrow D^*\pi)$, which is substantial (~ 100 MeV) for most of the allowed $\tilde{\beta}$ range. However, for the lower extremum $\Gamma(D' \rightarrow D^*\pi)$ is as low as 10 MeV. Assuming flavor SU(3) symmetry, we can also estimate $\Gamma(D' \rightarrow D^*\eta) = 20, 26$ MeV at the lower extremum [17]. Fixing from $\Gamma(K^*(1410) \rightarrow K\pi)$ we find that the sum of the decays to $D^*\pi$, $D^*\eta$ and D_s^*K can be as low as 7.9 MeV and consistent with the DELPHI total width for $0.13 \leq \tilde{\beta} \leq 0.20$, a region that is disjoint, but tantalizingly close, to the preferred region $0.21 \leq \tilde{\beta} \leq 0.25$ GeV. D' should hence be considered too wide to be in agreement with the DELPHI width, although this depends sensitively on the experimental data on $K^*(1410) \rightarrow K\pi$, $K^*\pi$.

D' , using $K'(1680)$. The ratio $\Gamma(K^*(1680) \rightarrow K\pi)/\Gamma(K^*(1680) \rightarrow K^*\pi)$ is $1.30_{-0.14}^{+0.23}$ (or 2.8 ± 1.1 directly from the LASS data) [3]. This ratio, together with $\Gamma(K^*(1680) \rightarrow K\pi)$ [16] is used to estimate $\Gamma(D' \rightarrow D^*\pi)$, and within SU(3) symmetry $\Gamma(D' \rightarrow D^*\eta, D_s^*K)$. We are able to find a total $D^*\pi$, $D^*\eta$ and D_s^*K width of less than 15 MeV only when we assume $\Gamma(K^*(1410) \rightarrow K\pi)/\Gamma(K^*(1410) \rightarrow K^*\pi) \geq 3.4$, consistent, but at the very edge of the LASS error bars. Consistency with the DELPHI bound is hence unnatural, but can be achieved.

In conclusion, except for D_3^* and $D_{2j_q=5/2}$ which are not assumed to have a nodal form factor, all interpretations of $D(2637)$ have too large a width, except possibly D' . This conclusion is contingent on our inability to calculate D' decays to $D_0^*\pi$, $D_{2j_q=5/2}\pi$, $D(\pi\pi)_S$ and $D\rho$ from heavy quark symmetry.

DELPHI made the preliminary claim of an enhancement at 5905 ± 11 MeV decaying probably to $B^*\pi^+\pi^-$ [18]. Given the similarity of this decay mode to the observation of $D(2637) \rightarrow D^*\pi^+\pi^-$ [1], we postulate that $B(5905)$ and $D(2637)$ are analogues of each other with different heavy quarks, and explore the consequences.

Up to $1/m_Q$ corrections to heavy quark symmetry, we can write for the mass of the heavy-light meson $B(5905)$ and $D(2637)$ [5,6]

$$\begin{aligned} M(B(5905)) &= M(1S)_B + E + C/m_b, \\ M(D(2637)) &= M(1S)_D + E + C/m_c \end{aligned} \quad (4)$$

where e.g. $M(1S)_B = (3M(B^*) + M(B))/4$ is the mass of the ground state. The efficacy of using the approach in Eq. (4) to

estimate heavy-light meson masses is seen by noting that, the predictions of this approach for $D_{sJ}(2573)$, $D_{s1}(2536)$, $B_J^*(5732)$ and $B_{sJ}^*(5850)$ [5,6] are in as good agreement with experiment as potential models [7,8,10]. The first set of charm and bottom quark masses is taken to be $m_c=1.48$ GeV, $m_b=4.8$ GeV; and the second set $m_c=1.84$ GeV, $m_b=5.18$ GeV, following Refs. [5,6]. These two sets of masses include most of the range found in potential models, particularly those of Refs. [7,8,14,15].

Using the analogous equations to Eq. (4) and following Refs. [5,6] by fitting $K_2^*(1430)$, $K_1(1270)$, $D_2^*(2460)$ and $D_1(2420)$ according to the newest PDG masses [3], one obtains $m_s=0.348$ GeV for set one and $m_s=0.433$ GeV for set two.

There are two equations in Eq. (4), which we solve for the two unknowns E and C . Substituting these values into the expression for the mass of the K-meson analogue of $B(5905)$ and $D(2637)$, $M(1S)_K+E+C/m_s$, we obtain the K-meson mass 1820 ± 60 MeV and 1850 ± 70 MeV for the first and second sets of m_s, m_c and m_b respectively.

In conclusion, assuming the validity of the masses of $B(5905)$ and $D(2637)$ from experiment, and that they are simply analogues of each other with different heavy quarks, the lowest order correction to heavy quark symmetry predicts that the K-meson analogue should have a mass of 1800 ± 60 MeV or 1820 ± 70 MeV. $K_3^*(1780)$, $K_2(1770)$ and $K_2(1820)$ are comfortably within, and $K^*(1680)$ at the edge of, these mass regions. Given that $D(2637)$ is an analogue of one of these states, the J^P of $D(2637)$ is 2^- , 3^- or possibly 1^- .

It is critical to corroborate the claim by DELPHI of such a small $D(2637)$ total width. The total width is more dis-

crimatory than individual partial widths, e.g. with the nodal form factor the decay $D_{1j_q=1/2}^*\rightarrow D^*\pi$ is small, but the collective decay to $D^*\pi$ and $D^*\eta$ is substantial. Dominant modes are likely to be $D\pi$, $D^*\pi$, $D^*(\pi\pi)_S$ and for some interpretations $D(\pi\pi)_S$. A small width for $D(2637)$ would put a restrictive bound on $D^*(\pi\pi)_S$, and for some interpretations on $D(\pi\pi)_S$. This would be a useful input into models. The J^P of $D(2637)$ can experimentally be ascertained without partial wave analysis. For example, of the possibilities considered only 0^- and 2^- should have enough phase space for the experimentally challenging decay to $D_0^*\pi$. Only 1^+ , 0^- and 2^- decay to $D(\pi\pi)_S$ and do not decay to $D\pi$, $D\eta$ and D_sK .

If the DELPHI mass and width of $D(2637)$ are confirmed, it would present a fascinating challenge for theory. Within heavy quark symmetry, the width cannot be explained by an exhaustive list of possibilities, except possibly if the state is D_3^* , $D_{2j_q=5/2}$ or D' . However, these possibilities are inconsistent with potential model mass estimates. Moreover, if $D(2637)$ is either D_3^* or $D_{2j_q=5/2}$ then it appears that the other (unobserved) resonance should appear within 20 MeV of it [7]. The interpretation of $D(2637)$ as D' is complicated by the fact that decay via the kinematically preferred route $D^*(\pi\pi)_S$ is not allowed. Since $D(2637)$ is observed in $D^*\pi\pi$, this would have to arise via kinematically suppressed routes like $D^*\rho$ and $D_2^*(2460)\pi$. Of the potentially narrow interpretations of $D(2637)$, D_3^* and $D_{2j_q=5/2}$ are preferred when the implications of the lowest order corrections to heavy quark symmetry on heavy-light meson masses are analyzed.

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