Possibility of Deeply Bound Hadronic Molecules from Single Pion Exchange

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(Received 1 April 2009; published 18 June 2009)

Pion exchange in an S wave between hadrons that are themselves in a relative S wave can shift energies by hundreds of MeV. In the case of charmed mesons D, D^*, D_0, D_1, a spectroscopy of quasimolecular states may arise consistent with enigmatic charmonium states observed above 4 GeV in e^+e^- annihilation. A possible explanation of $Y(4260) \to \psi\pi\pi$ and $Y(4360) \to \psi'\pi\pi$ is found. Searches in $D\bar{D}3\pi$ channels as well as B decays are recommended to test this hypothesis.

DOI: 10.1103/PhysRevLett.102.242003 PACS numbers: 12.39.−x, 13.75.Lb, 14.40.Gx, 21.30.Fe

The exchange of a π in an S wave between pairs of hadrons that are themselves in a relative S wave leads to deeply bound states between those hadrons. Examples of such spectroscopy appear to be manifested among charmed mesons. Here we summarize the general arguments and outline a program for both theoretical and experimental investigation.

If two hadrons A, B are linked by $A \to B\pi$, then necessarily hadronic pairs of AB or $A\bar{B}$ have the potential to feel a force from π exchange. This force will be attractive in at least some channels.

The most familiar example is the case of the nucleon, where $NN\pi$ coupling is the source of an attractive force that forms the deuteron. Long ago [1,2] the idea of π exchange between flavored mesons, in particular, charm, was suggested as a source of potential "deusons" [1]. Using the deuteron binding as normalization, the attractive force between the $J^P = 0^-$ charmed D and its $J^P = 1^-$ counterpart D^* was calculated for the $D\bar{D}^* + \text{c.c.}$ S wave combination with total $J^{PC} = 1^{++}$, and the results compared with the enigmatic charmonium state $X(3872)$ [1,3–5].

Instead of normalizing the pion coupling constant to the deuteron, it may be more directly parametrized by decay widths, for example, the observed width $\Gamma(D^* \to D\pi)$ [1,5]. Several groups have studied the following J^P channels looking for bound states in total J^{PC} channels due to pion exchange (from here on $D\bar{D}^*$, etc. will be taken to include the charge conjugate channel):

$$D^*(1^-) \to D(0^-)\pi \text{ leading to the deuson } \bar{D}D^*X(3872)J^{PC} = 1^{++},$$

$$D^*(1^-) \to D^*(1^-)\pi \text{ leading to the deusons } D^*\bar{D}^*J^{PC} = 0^{++}, 1^{+-}, 2^{++}.$$

These combinations were discussed in [1]. In all of these examples parity conservation requires that the π is emitted in a P wave; the hadrons involved at the emission vertices have their constituents in a relative s wave (we use S, P to denote the angular momentum between hadrons and s, p to denote internal angular momentum of the constituents within a hadron). In such cases, the π emission being in P wave causes a penalty for small momentum transfer $\mathbf{q}$, which is manifested by the interaction [6]

$$V_P(\mathbf{q}) = -\frac{g^2}{f_\pi^2}\frac{(\sigma_i \cdot \mathbf{q})(\sigma_j \cdot \mathbf{q})}{|\mathbf{q}|^2 + \mu^2}(\tau_i \cdot \tau_j), \qquad (1)$$

where $\mu^2 \equiv m_\pi^2 - (m_B - m_A)^2$, $m_{A,B}$ being the masses of the mesons in $A \to B\pi$. [For a discussion of this interaction, and its sign, see Eq. (20) in Ref. [5].] The resulting potential is $\propto \mathbf{q}^2$ for low momentum transfer and has been found to give bindings on the scale of a few MeV, which is in part a reflection of the P-wave penalty.

There is no such penalty when π emission is in an S wave, which is allowed when the hadrons A, B have opposite parities. Examples involving the lightest charmed mesons are $D_1(1^+) \to D^*(1^-)\pi$ and $D_0(0^+) \to D(0^-)\pi$. One might anticipate that the transition from a D or D^* with constituents in an s wave to the D_1 or D_0 where they are in a p wave would restore a penalty as $\mathbf{q} \to \mathbf{0}$, leading to small binding effects as in the cases previously considered. However, as we now argue, this need not be the case, and energy shifts of $\mathcal{O}(100)$ MeV can arise.

First, at a purely empirical level, the large widths [3] for $\Gamma(D_0 \to D\pi) \sim 260 \pm 50$ MeV and $\Gamma[D_1(2430) \to D^*\pi] \sim 385 \pm \mathcal{O}(100)$ MeV imply, even after phase space is taken into account, that there is a significant transition amplitude. The phenomenon of nonsuppression is well known for light hadrons and was specifically commented upon in the classic quark model paper of Ref. [7]. It arises from a derivative operator acting on the internal hadron wave function, which enables an internal s to p transition to occur even when the momentum transfer between the hadrons vanishes. This can be seen when $\bar{\psi}\gamma_5\psi$ is expanded to $\sigma \cdot (\mathbf{q} - \omega\mathbf{p}/m)$, where $\mathbf{q}$ is the three-momentum transfer and $\mathbf{p}$ the internal quark momentum [8]. Feynman *et al.* [7] argued for this on general grounds of Galilean invariance. The presence of $\mathbf{p}$ gives the required derivative operator, and hence the $p \to s$ transition.

In dynamical models of π emission, such as the $^3P_0$ model [9], a $q\bar{q}$ must be created: $q_i \to q_i\bar{q}q \to \pi(q_i\bar{q})q$. The creation operator is proportional to $\sigma \cdot \mathbf{p}$, where $\mathbf{p}$ is the momentum of the quark created in the $q\bar{q}$ pair, which goes into the p wave meson. In chiral perturbation theory [10] a similar result is found. When applied to π exchange in the D^*D_1 system (e.g., [11]) the analogue of Eq. (1) (as presented in Table 1 of Ref. [11]) becomes

$$V_S(\mathbf{q}) = \frac{h^2}{2f_\pi^2}\frac{(m_A - m_B)^2}{|\mathbf{q}|^2 + \mu^2}. \tag{2}$$

The absence of a $\mathbf{q}^2$ penalty factor is immediately apparent, the scale now being set by an energy gap squared, $(m_A - m_B)^2$.

Thus on rather general grounds we may anticipate significant energy shifts, $\sim\mathcal{O}(100\text{ MeV})$, due to π exchange at least in some channels between such hadrons in a relative S wave. Signals may be anticipated below or near threshold in the following channels (with manifest flavor, $I = 1$, or in the charmonium analogues, $I = 0$, involving charm and anticharm mesons):

$$D_0(0^+) \to D(0^-)\pi \text{ leading to the deusons } D\bar{D}_0 J^{PC} = 0^{-\pm},$$

$$D_1(1^+) \to D^*(1^-)\pi \text{ leading to the deusons } D^*\bar{D}_1 J^{PC} = (0, 1, 2)^{-\pm}.$$

Pion exchange depends on the presence of u, d flavors; therefore, there will be no such effects in the $D_s\bar{D}_s$ analogues. Further, the potential depends only on the quantum numbers of the light quarks. Therefore, there will be effects in the strange ($K\bar{K}$) and bottom ($B\bar{B}$) analogues, which can add to the test of such dynamics.

We shall illustrate our ideas with the case of charm and draw attention to possible signals for this dynamics. A variational calculation with the $I = 0$ analogue of the potential of [11] suggests binding of at least $\mathcal{O}(100)$ MeV is possible in the $I = 0$ 1^{--} $D^*\bar{D}_1$ channel. Hence, both the ground and first radially excited eigenstates may be bound. As we shall show, the $Y(4260) \to \psi\pi\pi$ and $Y(4360) \to \psi'\pi\pi$ are consistent with this picture. We now summarize the arguments that lead to this conclusion.

The $D_1\bar{D}^*$ (and charge conjugate) combination is interesting as the 1^{--} channel is accessible in e^+e^- annihilation [12]. In the chiral perturbation theory model, the Fourier transformed S-wave potential has the structure [11]

$$V_S(r) = \frac{h^2(m_A - m_B)^2}{8\pi f_\pi^2}\frac{\cos(|\mu|r)}{r}. \tag{3}$$

By extracting h directly from the $\Gamma(D_1 \to D^*\pi)$, following Eq. (137) of Ref. [13], we find $h = 0.8 \pm 0.1$ when $f_\pi = 132$ MeV. We confirm the conclusion of [11], that π exchange is unlikely to form a bound state in the 1^{--}, $I = 1$ channel.

For the $I = 0$ configuration things are radically changed. The $\langle\tau \cdot \tau\rangle$ is now of opposite sign and 3 times stronger than for $I = 1$. The opposite sign moreover causes the attractive well to occur in the leading $r \to 0$ part of $\cos(|\mu|r)/r$. Using a variational calculation we find a deep binding energy of $\mathcal{O}(100)$ MeV (Fig. 1) for the expectation value of the Hamiltonian with $\psi(r) = (1 + \alpha r^2)e^{-\beta r^2}$, where r is the radial separation of the D^* and D_1 mesons, and where these and the π are assumed to be pointlike. The variational principle only gives lower bounds on binding energies. A more quantitative study which explicitly solves the Schrödinger equation will be necessary for a precise estimate of the binding energy. The results are robust for a wide range of physical values of β, and they are only weakly dependent on α, hence not overly sensitive to smearing, such as when modeled by form factors. We have verified that bound states survive the *ad hoc* addition of a repulsive square well with a range of 1.25 GeV^{-1} and a magnitude up to 1 GeV. Further

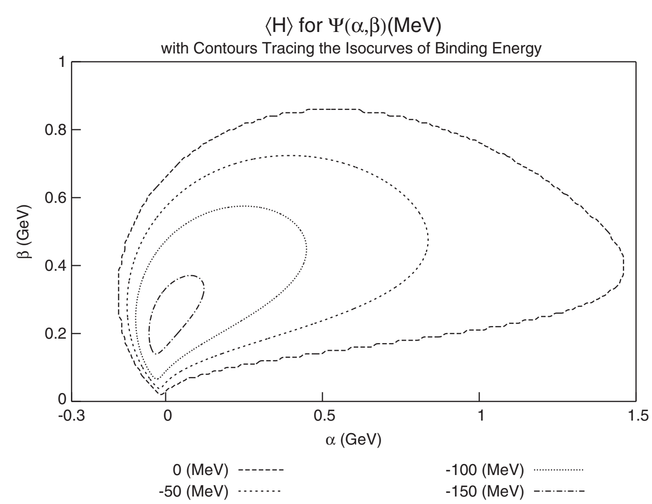

FIG. 1. The expectation value of the Hamiltonian with the $I = 0$ potential from [11] and a trial wave function $\psi(r) = (1 + \alpha r^2)e^{-\beta r^2}$.

model dependent studies could be made, but here we wish to focus on the general conclusions.

Given the depth of binding of the ground state with trial wave functions, there is the tantalizing possibility that a radially excited state could also be bound. As the excitation energy for radial excitation of a compact QCD $c\bar{c}$ state is $\mathcal{O}(500)$ MeV, it is possible that the extended molecular system may be excited by less, perhaps $\mathcal{O}(100)$ MeV. The rearrangement of constituents leading to final states of the form ψ + light mesons then rather naturally suggests that the lower (radial) state converts to $\psi\pi\pi$ ($\psi'\pi\pi$), respectively. In this context it is intriguing that there are states observed with energies and final states that appear to be consistent with this: $Y(4260) \to \psi\pi\pi$ [14] and the possible higher state $Y(4360) \to \psi'\pi\pi$ [15,16] are, respectively, 170 and 70 MeV below the $D^*(2010)\bar{D}_1(2420)$ combined masses of 4430 MeV.

If these states were to be established as such, one could tune the model accordingly. Further, this could be an interesting signal for a $D^*\bar{D}_1$ quasimolecular spectroscopy with transitions among states that could be revealed in, for example, $e^+e^- \to \psi\gamma\gamma\pi\pi$.

Note also that although the $Y(4260)$ is near the DD_1 and D^*D_0 S-wave thresholds, parity conservation forbids π exchange other than in the off diagonal $DD_1 \to D^*D_0$. Thus in contrast to the D^*D_1 system discussed here, π exchange is not expected to play a leading role in the DD_1 and D^*D_0 channels. As D^* and $D_0 \to D\pi$ whereas $D_1 \to D\pi\pi$, the $D^*\bar{D}_1$ bound state $\to D\bar{D}3\pi$ in contrast to DD_1 or $D^*D_0 \to D\bar{D}2\pi$. Thus an immediate consequence of this interpretation is that there must be significant coupling of the $Y(4260) \to D\bar{D}\pi\pi\pi$ that could exceed that to $D\bar{D}\pi\pi$.

In e^+e^- annihilation, the primary production is $\gamma \to c\bar{c}$ followed by hadronization. This only feeds the $I = 0$ sector. The $Y(4260)$ is seen also in $B \to KY(4260)$ [3,17]. This branching ratio sets the scale for the production of other states in $B \to KX$. The dynamical uncertainty is whether this production is driven by a direct production of two quarks and two antiquarks, or whether it is through a leading $c\bar{c}$ Fock state in the hadron wave function. In the latter case, only $I = 0$ combinations can be accessed; in effect this is like e^+e^- annihilation but with $b\bar{s} \to c\bar{c}$ in any of $J^P = 0^\pm, 1^\pm$. The $J^{PC} = 1^{-+}$ state can be produced via a $c\bar{c}$ hybrid Fock state. The relative branching ratio will depend on the relative importance of hybrid to conventional branching ratios in B decays [18].

Tantalizing signals for a possible resonant enhancement are seen in $B \to K\psi\omega$ immediately above threshold [19]. This decay channel is allowed for the $I = 0$ attractive combinations in $J^{PC} = (0, 1, 2)^{-+}$. We advocate that structures in $B \to K\psi\omega$ be investigated and their J^P determined.

Since the attraction of the potential depends only on the quantum numbers of the light $q\bar{q}$, it follows immediately that the flavor of the heavy quarks is irrelevant. Hence we expect similar effects to occur in the $b\bar{b}$ and $s\bar{s}$ sectors. It has been noted that $\Upsilon(10.86)$ GeV appears to have an anomalous affinity for $\Upsilon\pi\pi$ [20]. This state is $\sim$130 MeV below $B^*\bar{B}_1$ threshold. In the $\phi\pi\pi$ channel there is an enhancement at 2175 MeV [21]. This is approximately 125 MeV below the $K^*\bar{K}_1(1400)$ threshold. Analysis here is more complex as the heavy quark approximation fails, and the phenomenology of the $K_1(1270; 1400)$ pair is more complicated [22,23].

From theoretical and empirical studies of hadronic decay widths, one would expect strong S-wave pion exchange effects to occur. These effects would be manifested in analogous ways in the strange, charm, and bottom sectors and would provide natural explanation for some of the new charmonium states. The number of bound states and the precise values of their energies will be model dependent, but the deep binding from S wave pion exchange should be a general result. The main quantitative uncertainty is the experimental value for $\Gamma(D_1 \to D^*\pi)$, which sets the scale for $V_S(r)$. Nonetheless, if π exchange occurs, the presence of deep binding in some channels seems unavoidable. If this is not seen, it will have significant implications for the hypothesis of π exchange as a hadronic interaction.

Further theoretical investigation is merited, in particular, the roles of form factors, sensitivity to parameters, the absorptive part of the potential due to the on-shell pion contribution, and to other short-range forces. The physical decay of the D_1 into a $D^*\pi$ means that the bound state disintegrates, or even that it fails to form. Thus, we expect the on shell pion contribution will endow any state produced by this mechanism with a width, or that it produces a nonresonant background which may obscure the signal. However, our first survey suggests that the long-range virtual π exchange in an S wave gives a powerful attractive force, and that examples of such a spectroscopy do appear to be manifested.

One of us (F. E. C.) thanks Jo Dudek for a question at a Jefferson Lab seminar which stimulated some of this work and T. Burns for discussion. We would like to thank C. Thomas for comments on a draft of this work and Dr. Yan Rui Liu for pointing out a typo. This work is supported by grants from the Science & Technology Facilities Council (U.K.) and in part by the EU Contract No. MRTN-CT-2006-035482, "FLAVIAnet."

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