# Possible Large Deuteronlike Meson-Meson States Bound by Pions

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Using the analogy of the deuteron, spin-flavor symmetry, statistics, etc., it is argued that the one-pion exchange potential is likely to bind a few states composed of two ground-state mesons. The best $S$-wave candidates have masses, quantum numbers, and decay widths similar to those observed for the experimentally best established non-$q\bar{q}$ candidates: $\theta/f_0(1720)$, $G/f_0(1590)$, $A_X/f_2(1520)$, and $E/f_1(1420)$. Possible $P$-wave states are the $\eta(1410)$ and $\eta(1490)$. Also the threshold enhancements seen in $J/\psi \to \gamma\rho\rho, \gamma\omega\omega, \gamma K^*\bar{K}^*$ and in $\gamma\gamma \to \rho\rho$ are likely to be involved.

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Since Yukawa [1] predicted the pion it has become very well known that the deuteron and nucleons in general can be well described as bound states formed by the exchange of mesons, most importantly the pion. Recall the long-range one-pion exchange potential (OPEP) [2],

$$V(r) = \frac{f^2}{3}\left[(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)(\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2) + S_{12}(\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2)\left(1+\frac{3}{\mu r}+\frac{3}{(\mu r)^2}\right)\right]\frac{e^{-\mu r}}{r}, \tag{1}$$

where in the second tensor term $S_{12} = 3(\boldsymbol{\sigma}_1\cdot\mathbf{r})(\boldsymbol{\sigma}_2\cdot\mathbf{r})/r^2 - \boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2$. Recall also that as a first approximation the spin-isospin factor $(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)(\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2)$ gives the main attraction in the $NN$ (spin $S=1$, isospin $I=0$, ${}^3S_1$) deuteron channel, being $-3$, whereas for the other quantum numbers $(1,1,{}^3P_J)$, $(0,0,{}^1P_1)$, and $(0,1,{}^1S_0)$ it is $+1$, $+9$, and $-3$, respectively. The attraction in the deuteron channel is strengthened by the tensor term to actually form the deuteron with its ${}^3D_1$ component, in contrast to the ${}^1S_0$ state which is only very close to forming a bound state.

It is natural to ask: Can the OPEP also bind mesons when $\pi$ exchange is allowed? And could such states possibly explain the growing number of experimentally seen mesonic states which do not fit into the conventional $q\bar{q}$ quark model [3]? In this Letter I show that out of the large number of potential meson-meson combinations (81 for two different nonets) pions can bind only a few, but that for these the binding can be quite strong. Using the analogy of the above simple arguments for the deuteron as a guide it seems very likely that such bound states exist. Below I shall refer to such deuteronlike meson-meson bound states as *deusons*.

My arguments can only be plausibility arguments, since a full treatment of the problem would involve detailed calculations including the tensor term, coupled-channel effects, two-pion exchange, short-range attraction or repulsion from heavier-meson exchanges, etc., which are clearly outside the scope of this Letter. But, as we shall see, the OPEP approximation discussed here gives strong attraction in precisely those channels where we have good experimental candidates for non-$q\bar{q}$ states. It is therefore hoped that these results will attract interest to perform more detailed analyses. Much effort has been given to understand the non-$q\bar{q}$ states as glueballs, $q\bar{q}g$ hybrids, diquonium, or four-quark states, etc., whereas more conventional forms of bound states have been neglected. Exceptions are Longacre's [4] paper on $K\bar{K}\pi$-molecule interpretation of the $E/f_1(1420)$, and Dover's [5] attempt to understand the $A_X/f_2(1520)$ as a "quasinuclear $N\bar{N}$ bound state."

Since the pion is very light, deusons could be much larger than ordinary mesons, by a factor of $m_\rho/m_\pi \approx 5$. Thus one could expect large states of up to even 3 fm in size or larger than the deuteron, and much larger than conventional $q\bar{q}$ mesons. In reality, when there is also short-range attraction, a size in the intermediate region 1-2 fm is more likely. Being loosely bound large states their masses should be close to the sum of their constituent meson masses and their decay and production properties quite different from conventional $q\bar{q}$ mesons.

Which are the lightest deusons expected? Obviously two-pseudoscalar ($P$) bound states ($PP$) are excluded by parity. Restricting ourselves to ground-state mesons [$P$ and $V$ (vector meson)], only $PV$ and $VV$ states are possible. Thus deusons are different from the suggested [6] "$K\bar{K}$ molecules" for $a_0(980)$ and $f_0(975)$, which require a large quark-spin hyperfine interaction for the binding. Previously I suggested [7] an alternative scheme for understanding these light scalars.

*VV S-wave deusons.*—Of all $\pi VV$ coupling constants only the $\pi\rho\omega$ and the $\pi\bar{K}^*K^*$ are nonvanishing by flavor symmetry, the Okubo-Zweig-Iizuka rule, and $C$ parity. These constraints are most easily summarized by the factor $\mathrm{Tr}[M_1M_2M_3]_+$, where the $M_i$'s are $3\times 3$ flavor matrices for the nonets. Therefore, only the $K^*K^*$, $K^*\bar{K}^*$, $\omega\rho$, $\sqrt{1/2}(\omega\omega \pm \rho\rho)_{I=0}$, and $\sqrt{1/2}(K^*\omega \pm K^*\rho)_{I=1/2}$ states are possible candidates (cf. Table I). The Born terms for $\pi$ exchange for these cases are shown in Figs. 1(a)-1(d). Many of the $VV$ combinations, in particular most exotic ones, are already excluded.

A simple way to obtain the spin-dependent factor for $K^*K^*$ is to substitute $\boldsymbol{\sigma}_1 \to \boldsymbol{\epsilon}_1\times\boldsymbol{\epsilon}_1'^*$ and $\boldsymbol{\sigma}_2 \to \boldsymbol{\epsilon}_2'^*\times\boldsymbol{\epsilon}_2$ in Eq. (1) [see Fig. 1(a) for the notation]. One finds that

TABLE I. The spin and internal symmetry factors for the possible $VV$ deusons. The normalization is such that the $\pi^0 K^{*+} K^{*-}$ vertex is $+1$. The RBN (relative binding number) column is the product of the two previous columns and is a measure for the strength of the binding. When RBN is the most negative one expects the largest binding. The experimental non-$q\bar{q}$ candidates are mentioned in the comment column.

| State, threshold, sum of widths | $S$ | $I$ | Spin factor | $SU(3)_f$ factor | RBN | Comment |
|---|---|---|---|---|---|---|
| $K^*K^*$, | 0 | 0 | $-2$ | $-3$ | $+6$ | $L$=odd |
| 1790 MeV, | 1 | 0 | $-1$ | $-3$ | $+3$ | |
| $\Gamma > 103$ MeV | 2 | 0 | $+1$ | $-3$ | $-3$ | $L$=odd |
| | 0 | 1 | $-2$ | $+1$ | $-2$ | |
| | 1 | 1 | $-1$ | $+1$ | $-1$ | $L$=odd |
| | 2 | 1 | $+1$ | $+1$ | $+1$ | |
| $K^*\bar{K}^*$, | 0 | 0 | $+2$ | $-3$ | $-6$ | $\theta/f_0(1720)$ |
| 1790 MeV, | 1 | 0 | $+1$ | $-3$ | $-3$ | |
| $\Gamma > 103$ MeV | 2 | 0 | $-1$ | $-3$ | $+3$ | |
| | 0 | 1 | $+2$ | $+1$ | $+2$ | |
| | 1 | 1 | $+1$ | $+1$ | $+1$ | |
| | 2 | 1 | $-1$ | $+1$ | $-1$ | |
| $\rho\omega$, | 0 | 1 | $+2$ | $+4$ | $+8$ | |
| 1553 MeV, | 1 | 1 | $+1$ | $+4$ | $+4$ | |
| $\Gamma > 158$ MeV | 2 | 1 | $-1$ | $+4$ | $-4$ | |
| $(\omega\omega-\rho\rho)/\sqrt{2}$, | 0 | 0 | $+2$ | $-4\sqrt{3}$ | $-8\sqrt{3}$ | $G/f_0(1587)$ |
| 1553 MeV, | 1 | 0 | $+1$ | $-4\sqrt{3}$ | $-4\sqrt{3}$ | $L=1$, $\eta(1490)$ |
| $\Gamma > 158$ MeV | 2 | 0 | $-1$ | $-4\sqrt{3}$ | $+4\sqrt{3}$ | |
| $(\omega\omega+\rho\rho)/\sqrt{2}$, | 0 | 0 | $+2$ | $+4\sqrt{3}$ | $+8\sqrt{3}$ | |
| 1553 MeV, | 1 | 0 | $+1$ | $+4\sqrt{3}$ | $+4\sqrt{3}$ | $L$=odd |
| $\Gamma > 158$ MeV | 2 | 0 | $-1$ | $+4\sqrt{3}$ | $-4\sqrt{3}$ | $A_X/f_2(1520)$ |
| $(K^*\omega-K^*\rho)/\sqrt{2}$, | 0 | $\frac{1}{2}$ | $+2$ | $-2\sqrt{3}$ | $-4\sqrt{3}$ | New state |
| 1670 MeV, | 1 | $\frac{1}{2}$ | $+1$ | $-2\sqrt{3}$ | $-2\sqrt{3}$ | |
| $\Gamma > 129$ MeV | 2 | $\frac{1}{2}$ | $-1$ | $-2\sqrt{3}$ | $+2\sqrt{3}$ | |
| $(K^*\omega+K^*\rho)/\sqrt{2}$, | 0 | $\frac{1}{2}$ | $+2$ | $+2\sqrt{3}$ | $+4\sqrt{3}$ | |
| 1670 MeV, | 1 | $\frac{1}{2}$ | $+1$ | $+2\sqrt{3}$ | $+2\sqrt{3}$ | |
| $\Gamma > 129$ MeV | 2 | $\frac{1}{2}$ | $-1$ | $+2\sqrt{3}$ | $-2\sqrt{3}$ | |

the spin-dependent factor gives the ratios $-2:-1:1$ for the total spins $S=0,1,2$, respectively, for the sum of two vector meson spins. Another way to get the same numbers is to use the general formula $\mathbf{S}_1\cdot\mathbf{S}_2=\frac{1}{2}[(\mathbf{S}_1+\mathbf{S}_2)^2-\mathbf{S}_1^2-\mathbf{S}_2^2]$.

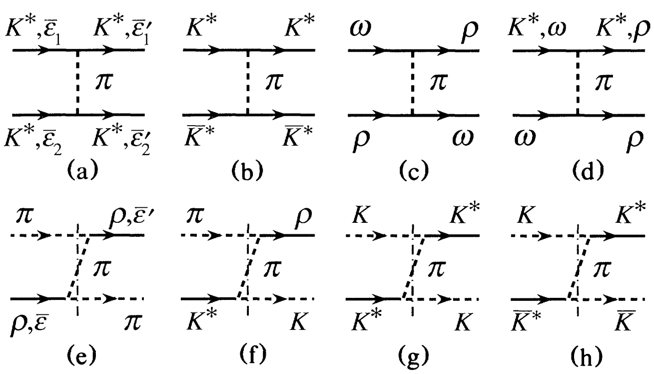


FIG. 1. The Born term diagrams with $\pi$ exchange for (a)–(d) the $VV$ states and (e)–(h) the $PV$ states.

Table I lists the values of the spin and internal symmetry factors (crossing matrix elements), whose product gives an indication of which states are expected to be bound; the more negative the number, the stronger the binding. We refer to this number below as the relative binding number (RBN).

It is interesting that the quantum numbers for essentially all of the $S$-wave states which have the largest negative RBN turn out to be precisely those for which we have [3] the best experimental non-$q\bar{q}$ candidates.

In $K^*\bar{K}^*$ there is the strongest binding (RBN equal to $-6$) for $I^G=0^+$, $J^{PC}=0^{++}$, where there is the well-known "glueball candidate" $\theta/f_0(1720)$, whose spin recently has been shown to be 0 and not 2 [8]. It is, in fact, crucial for our scheme that this spin actually is verified to be $0^{++}$, since the $S=2$, $I=0$, $S$-wave, $2^{++}$ deuson channel is repulsive. A spin-2 $K^*\bar{K}^*$ deuson would require the $D$ wave to be important.

For $(\omega\omega-\rho\rho)/\sqrt{2}$ one also gets strong binding (RBN equal to $-8\sqrt{3}$) for $I^G=0^+$, $J^{PC}=0^{++}$ which could be the $G/f_0(1587)$ seen by the GAMS Collaboration [9].

This resonance does not fit as a $q\bar{q}$ state, and is often quoted as being a glueball candidate. For $S=1$, RBN is equal to $-4\sqrt{3}$ but Bose symmetry requires odd $L$. Possibly the $^3P_0$ state could be one of the $\eta$'s in the iota peak (see below).

A third strong binding (RBN equal to $-4\sqrt{3}$) is found in $(\omega\omega+\rho\rho)/\sqrt{2}$ for $I^G=0^+$, $J^{PC}=2^{++}$ where we have the recently rediscovered $A_X/f_2(1520)$ by the ASTERIX Collaboration [10]. Its mass is better determined in the $3\pi^0$ channel and the new mass, 1520 MeV, agrees well with that which was seen previously [11,12].

These three resonances lie precisely as they should, a little below or close to the two-meson thresholds in question; i.e., $K^*\bar{K}^*$ at 1790 MeV, $\rho\rho$ at 1540 MeV, or $\omega\omega$ at 1566 MeV. Of course, naively one expects the binding energy to give a mass below these thresholds, whereas the $G/f_0(1587)$ would be slightly above. However, more detailed models including coupled-channel effects can easily shift the mass.

There remains in Table I essentially only one predicted additional deuson with large binding (RBN equal to $-4\sqrt{3}$): a $(K^*\omega-K^*\rho)/\sqrt{2}$ state with $I=\frac{1}{2}$, $J^P=0^+$. The mass of this resonance is expected near 1670 MeV, i.e., on top of the broad $K_1^*(1680)$ structure. However, its coupling to $K\pi$ and $K\pi\pi$ should be suppressed compared to $K^*\rho$ and $K^*\omega$ for the same reason as the form-factor argument given below, and has therefore been difficult to produce in current experiments. Its verification, e.g., in $N\bar{N}$ annihilation in flight would be strong support for the deuson model.

In addition, there are a few possible deuson candidates which have a less negative RBN (see Table I) and for which it is difficult to argue that they actually can be bound. In $K^*K^*$ there are two states (with RBN of $-3$ and $-2$, respectively) of which the first must had odd $L$, i.e., it is not an $S$-wave state. As these are in a flavor-exotic channel one expects a strong short-range repulsion from non-$\pi$ exchange. Therefore, a good guess is that they are not bound. In $K^*\bar{K}^*$, $I=0$ and $J=1$, the RBN is also $-3$ and thus one might have an extra $1^{++}$ state in the $\theta$ mass region. In $\omega\rho$, $I=1$ and $J=2$, the RBN is as large as $-4$. This could be bound, but would fall on top of the $A_X/f_2$ resonance for which we already found a place above. Only the isospin of this deuson would be different, which is not that well determined experimentally for the $A_X/f_2$, i.e., there may be two deusons at the $A_X/f_2$ mass. In fact, Bridges *et al.* [11] do see a peak in the $3\pi$ spectrum at 1480 MeV. In $(K^*\omega\pm K^*\rho)/\sqrt{2}$, $J=2$ and $J=1$, the RBN is $-2\sqrt{3}$ and these would be new predictions, but as equally hard to form in the current experiments as the more stronger bound $I=\frac{1}{2}$ state already discussed.

Finally, with charm and $b$ flavor one expects the partners of the $\theta/f_0$ just below the $D^*\bar{D}^*$ and $B^*\bar{B}^*$ thresholds. These would both be narrow, but difficult to produce because of quantum numbers and form factors, except perhaps in $N\bar{N}$.

*Widths and suppression of partial widths.*—The total widths of the three above candidates are not inconsistent with what would be expected if the decay of their constituent mesons are important when kinematically allowed. For the $\theta/f_0(1720)$ the experimental $\Gamma_\theta^{\rm expt}=138\pm12$ MeV is well above the bound $\Gamma_\theta\gtrsim\Gamma_{K^*\bar{K}^*}\approx2\Gamma_{K^*}=103$ MeV one would obtain if one neglects the kinematic suppression from the binding energy. For the $G/f_0(1587)$ and $A_X/f_2(1520)$ one would correspondingly have $\Gamma_{\rho\rho+\omega\omega}\approx\Gamma_\omega+\Gamma_\rho=158$ MeV which is consistent with the experimental total widths, $\Gamma_G^{\rm expt}=175\pm19$ MeV and $\Gamma_{A_X}^{\rm expt}=170\pm20$ MeV. For the $G$ we do not know experimentally the $\rho\rho,\omega\omega$ branching ratios, but their determination would be a good test of whether this candidate actually is a deuson. For $A_X/f_2(1520)$ the $\rho\rho$ width is known to be dominant [11,12] as we expect. Note that deuson decays naturally violate flavor-symmetry predictions, but not isospin.

An important prediction is that deuson decays to channels with large phase space should be strongly suppressed. Such a decay generally requires the exchange of heavier mesons than the $\pi$ (at least the $K$ or the $\eta$) and are therefore naturally suppressed. More importantly, as they are large in size they must have a steeply falling form factor in $k$ space. For normal $q\bar{q}$ states one has a form factor falling like $\exp(-k^2/k_0^2)$, with $k_0$ experimentally about 0.9 GeV [13]. This agrees well with the quark-pair-creation model prediction [14] of $k_0^2=8(R_1^2+R_2^2+R_3^2)/R_1^2(R_2^2+R_3^2)$ with meson radii of about 0.75 fm. But for the large deuson states one expects a much faster falling form factor with $k_0$ now determined mainly by the large size of the deuson. This suppresses all channels with large phase space, predicting, e.g., small $\theta\to\pi\pi/K\bar{K}$, $G\to\pi\pi/\eta\eta'$, and $A_X\to\pi\pi/\rho\rho$ in agreement with experiment.

Within another model assuming the $\theta$ to be a large glueball, Liu and Li [15] invoked a similar mechanism to understand the small $\pi\pi/K\bar{K}$ branching ratio, which violates naive predictions for a flavor-singlet decay.

*PV S-wave states.*—Turning to the possible $PV$ deuson candidates, one observes that only the $\pi\pi\rho$ and $\pi K\bar{K}^*$ couplings are nonvanishing, as easily verified from the factor $\mathrm{Tr}[M_1M_2M_3]_-$. Therefore we need only consider $\pi\rho$, $(\pi K^*\pm K\rho)/\sqrt{2}$, $KK^*$, and $(K\bar{K}^*\pm\bar{K}K^*)/\sqrt{2}$ [cf. Figs. 1(e)-1(h)]. However, these have features different from the previous candidates. (i) One can cut the Born-term diagram [as in Figs. 1(e)-1(h)] along the pseudoscalar lines and put the exchanged $\pi$ on shell, since the mass of the deuson candidate would be greater than the sum of the three pseudoscalar masses. This always gives a repulsive contribution canceling at least part of any binding from virtual pions. (ii) If one of the constituents is the pion itself, the reduced mass of the system is much smaller than otherwise, which increases the expected size of any bound state. The bound state would be larger than the range of the potential.

Because of these arguments it is unlikely that deusons which would have the pion itself as a constituent could form bound states, and in fact there are no experimental candidates. This leaves only the $KK^*$ and $(K\bar{K}^* \pm \bar{K}K^*)/\sqrt{2}$ as possible deuson systems. The spin-isospin factor is now $\pm(\epsilon\cdot\epsilon'^*)(\sigma_1\cdot\sigma_2)$ [Fig. 1(e)], being $\mp 3$ for $I=0$ and $\pm 1$ for $I=1$. Only $(K\bar{K}^*+\bar{K}K^*)/\sqrt{2}$ with $I=0$ has a reasonably strong binding (RBN equal to $-3$) to overcome the repulsion discussed above. This means, in the $S$ wave, a $J^{PC}=1^{++}$ state for which there is an obvious candidate: the $E/f_1(1420)$ lying, as it should, close to the $\bar{K}K^*$ threshold 1390 MeV. It has an experimental width $\Gamma_E^{\rm expt}=55\pm 3$ MeV which fits well the prediction of being slightly larger than the sum of the constituent widths or in this case $\Gamma_{K^*}=51.3\pm 0.8$ MeV. This picture agrees with Longacre's [4] more detailed model calculation, although he did not emphasize pion exchange. In fact, he found heavier-meson exchanges and other components in the wave function to be at least of equal importance. It has been shown [16] that the $E$ cannot be the $q\bar{q}$-model $s\bar{s}$ state [for which $f_1(1512)$ is a good candidate], perhaps most importantly because of its nonobservation in the $\gamma\phi$ mode.

*Possible P-wave and other deuson candidates.*— If one allows for higher angular momentum, the spectroscopy becomes more complicated, and more detailed model calculations are necessary to reach firm conclusions. Natural $^3P_0$ candidates are the $\eta(1410)$ and $\eta(1490)$ which could be (mixtures of) a $K\bar{K}^*$ and a $(\omega\omega-\rho\rho)/\sqrt{2}$ $P$-wave deuson. The two $\eta$'s belong to the iota peak, which probably [8,17] is composed of three resonances: the two $\eta$'s and the $E/f_1(1420)$.

Finally, a natural place to expect deusons to play a role is in the not well understood threshold enhancement in $\gamma\gamma\to\rho\rho$ [18] and the many peaks seen in $J/\psi\to\gamma\rho\rho$, $\gamma\omega\omega$, and $\gamma K^*\bar{K}^*$ [19]. There could perhaps even be radial excitations or at least threshold enhancements from "nearly bound deuson states." However, if this is so, isoscalar mesonic exchanges must be invoked to understand the $\phi\phi$ peaks seen in $\gamma\phi\phi$.

*Concluding remarks.*— As we have seen, the hypothesis that there exists large deuteronlike binding between vector mesons and $K\bar{K}^*$ mesons has the potential of being able to incorporate essentially all of our best non-$q\bar{q}$ candidates below 2 GeV. No superfluous states are predicted which should have been seen, but the prediction of a strange $I=\frac{1}{2}$ state coupling mainly to $K^*\omega$ and $K^*\rho$ should be looked for. The spin of the $\theta/f_0(1720)$ is also crucial and its verification of being mostly 0 and not 2 would be important. The fact that the masses and widths of four of our best non-$q\bar{q}$ candidates, $\theta/f_0(1720)$, $A_X/f_2(1520)$, $G/f_0(1590)$, and $E/f_1(1420)$, are predicted approximately correctly is an indication that the ideas presented are correct.

Clearly many of my arguments are only qualitative, and should be corroborated with detailed model calculations. If the scenario presented here turns out to be correct, it opens up a new interesting spectroscopy and new applications for nuclear physicists well acquainted with models for nuclear binding.

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