Comment on the new $D_s^{(*)+}\pi^0$ resonances

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We propose an explanation of the new resonances observed in $D_s^{(*)+}\pi^0$ decays. We suggest that the data can be explained by the mixing of conventional p-wave excited $D_s^+$ mesons with 4-quark states. The narrow states observed in $D_s^+\pi^0$ and $D_s^{*+}\pi^0$ are primarily p-wave $D_{sJ}^*$ states, while the predominantly 4-quark states are shifted above $D^{(*)}K$ threshold and should be broad. Ranges for the mixing parameter and mass of the 4-quark state in this scenario are given. Other experimental consequences are discussed.

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Meson spectroscopy is an important laboratory for understanding quark confinement. Mesons containing one heavy quark can provide invaluable information about the structure of the QCD Lagrangian, as spectroscopic considerations simplify significantly in the limit of infinitely heavy quark. In this limit the heavy quark spin $S_Q$ decouples, so the total angular momentum of the light degrees of freedom $J_q$ becomes a “good” quantum number. This leads to an important prediction of heavy quark symmetry: the appearance of heavy meson states in the form of degenerate parity doublets classified by the total angular momentum of the light degrees of freedom. This mass degeneracy is lifted with the inclusion of subleading $1/m_Q$ corrections. This useful picture is built into many quark-model descriptions of heavy meson spectra. The resulting models have been very successful in explaining the spectrum of negative-parity scalar and vector mesons. In addition, a second narrow state $D_{sJ}^*$ appears surprisingly low for quark model practitioners. In fact, its mass disagrees with most existing predictions of quark models. For example, a mass of 2487 MeV is obtained in the recent potential model calculation by Eichten and Di Pierro. Quenched lattice calculations also seem to favor larger values of the mass of this state (see, however, [12]). This led to a lively discussion of the possible non-$q\bar{q}$ nature of this state [13, 14, 15, 16]. In addition, a second narrow state is observed in $D_s^{(*)+}\pi^0$ at a mass near 2460 MeV. This state would naturally be identified as a spin 1 positive-parity p-wave meson. However, its mass also appears too low for the potential model expectations (e.g. 2605 MeV).

The observed low values of the masses for these states, however, do not signal a breakdown of quark-model descriptions of the heavy meson spectrum, as it is difficult to assess the accuracy of these predictions, especially in the charm sector. Many authors make use of the non-relativistic nature of the charm quark, taking into account $1/m_c$ corrections only. For the $0^+$ state, quark model predictions range from the values of 2387 – 2395 MeV (still above the DK threshold) on the low end of the spectrum to 2508 MeV on the high end. Since the described phenomena are highly non-perturbative, one should be careful before making a judgment on the nature of a given state based solely on the prediction of a given quark model. For example, as discussed above, in the $m_c \to \infty$ limit the $0^+$ and $1^+$ states are expected to become degenerate in mass, $m_{0^+}, m_{1^+} \to M$. This can be emulated in quark models by neglecting heavy-quark symmetry-violating $1/m_c$ corrections. Yet, different quark models predict very different behavior in this “heavy-quark limit”: for instance, one potential model predicts that the mass $M$ of the $(0^+, 1^+)$ multiplet will decrease to approximately 2382 MeV (which is less than the mass of the $0^+$ state predicted in this model with the full
potential), while in a QCD string model it is expected to increase up to 2500 MeV (which is much greater than the mass of the 0+ state predicted in this model with the full potential). In addition, quark models, modified to include chiral symmetry constraints, generally predicted lower values of mass splitting between (0−, 1+ ) and (0+, 1+) multiplets, of the order of 200−300 MeV. Nevertheless, the fact that the new state appears below DK threshold and is almost degenerate with a non-strange 0+ p-wave D state is curious and deserves an investigation.

It has been shown that the proper description of the low lying scalar mesons requires the inclusion of the coupling of the scalar qq states to the s-wave meson-meson channel, and this coupling is very important. By an extension of this argument, we would expect the scalar 0+ c\bar{s} state to mix with the DK s-wave state near threshold. This mixing can occur quite naturally if the states have the same quantum numbers (for instance, via the common intermediate states, see Fig. 1) and could shift the mass of the c\bar{s} state.

Alternatively, the possibility of 4-quark states with quark content c\bar{s}q\bar{q} has been discussed in the past. Here we consider the possibility that there is a 4-quark state that mixes with the c\bar{s} state and shifts its mass below DK threshold.

\[ m_1 = \frac{1}{2} \Sigma + \frac{1}{2} \sqrt{\Delta^2 + 4\delta^2} \]
\[ m_2 = \frac{1}{2} \Sigma - \frac{1}{2} \sqrt{\Delta^2 + 4\delta^2} \]

where \( \Sigma = m_0 + \bar{m}_0 \) and \( \Delta = m_0 - \bar{m}_0 \). The mixing angle that defines the composition of resulting mass eigenstates in terms of the original qq and q\bar{q} states is given by \( \tan(2\theta) = 2\delta/\Delta \).

Let us be more specific. For example, take \( \bar{m}_0 \) the bare mass of the 4-quark state to be just above DK threshold at 2.37 GeV and \( m_0 \) at the value 2.48 GeV as given by the potential model; then for a mixing parameter \( \delta \) of 0.092 GeV, we find two mixed states with masses \( m_2 = 2.3194 \) GeV and \( m_1 = 2.5375 \) GeV. The corresponding mixing angle is 28.8°. The lower state, which is dominantly a p-wave \( D_s \) meson, is below DK threshold, 2.358 GeV, but above \( D_s \) threshold, 2.103 GeV. Conversely, the higher state, which is dominantly a 4-quark system, is above DK threshold and is broad. There is a large set of parameters for the bare 4 quark mass and mixing that can shift the mass of the \( D^*_s \) to the observed value of 2317 GeV. This is illustrated in Figure 2. If \( m_0 \) is too high, it is difficult to shift the \( D^*_s \), state with a reasonable amount of mixing.

In principle, we also expect the same type of mixing to occur for the 1+ state. For instance, a molecular-type bound-state of \( D^*K \) of the kind suggested by Lipkin and others, can mix with the c\bar{s} \( ^3P_1 \) state and shift the 1+ states as well. To calculate the allowed range of mixing in this case is more complicated since there is mixing between the two 1+ states in addition to the mixing between the lower 1+ state and the relevant 4 quark state, and we do not attempt a detailed fit.

The properties and decay modes of the lower mixed states should be very similar to those expected for p-wave \( D_s \) mesons. Like the broad \( D^{**} \) states perhaps some of the additional states may be identified in exclusive B decays such as \( B \to D^{(*)0} D^0 K \) with enough statistics. The observation of these extra states could lend extra support for the existence of the multiquark and/or molecular states.
The 4 quark states can also give rise to very distinctive final states that are doubly charged \[20, 21\]. For example, there may be \( I = 1 \) states including a doubly charged state and a neutral state with decay modes into \( D^+K^+ \), etc. In the scenario described here, these exotic final states are above \( D^sK \) threshold and are therefore quite broad, experimentally difficult to find or even may be non-existent as "real" bound states. Note that we do not expect narrow doubly charged \( D^s\pi^+ \) or \( D^s\pi^- \) states in the scenarios described above.

It has also been suggested \[13, 22\] that radiative transitions of the type \( D_s^*(2317) \rightarrow D_s^*\gamma \) could be used to test the nature of these states. In particular, it was suggested that a very small branching ratio for the radiative decays would be an indication of a non-\( q \bar{q} \) nature of these states. In the scheme described above this test will be useful only for very small or very large (about \( \pi/2 \)) values of the mixing angle between \( c\bar{s} \) and \( c\bar{s}q \bar{q} \) states, as the contribution of \( c\bar{s}q \bar{q} \rightarrow D_s^*\gamma \) transition is suppressed by \( \sin \theta \). This is not so for moderate values of the mixing angle \[23\].

![Graph: \( \delta \) versus \( \tilde{m}_0 \) for solutions that satisfy the constraints of this scenario.](attachment:image.png)

FIG. 2: \( \delta \) versus \( \tilde{m}_0 \) for solutions that satisfy the constraints of this scenario.

In conclusion, we propose that the new states observed in \( D_{s\pi}^{0} \) and \( D_{s\pi}^{\ast 0} \) are shifted by mixing with 4-quark states. We expect that the observed states will have properties similar to those expected for \( p \)-wave \( D_s \) mesons except for their masses. The additional states responsible for the mixing and mass shifts will be above \( D^{(s)}K \) threshold and have large widths.

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