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Exes and why Z?
Some charming and beautiful observations.

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Threshold enhancements like the $X(4660)$ and depletion effects as the $X(4260)$ are listed as $c\bar{c}$ resonances in the Particle Data Group tables. We will discuss these observations, and present a list of further $c\bar{c}$ enhancements, which are more likely to represent true vector charmonium excitations.

We will furthermore discuss the importance of the observed Z resonances, viz. $Z(4050)$, $Z(4250)$, and $Z(4430)$, for the family of charm-strange mesons.

Another piece of very important information that can be extracted from the present data is the universal, flavor independent frequency of 190 MeV for mesons, due to the quark-antiquark oscillations within the glue environment.

Finally, we will show hints from the data at a further flavor-independent quantity, having a value of 76±2 MeV, the origin of which is not yet understood.

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In the recent past, we have developed a powerful formalism that does not necessarily rely on a specific choice for the dynamics of the quark-antiquark system, and which may reproduce the observed cross sections in meson-meson scattering [1] and in electron-positron annihilation reactions [2]. It is based on the assumption that observed structures in non-exotic meson-meson scattering and production are dominated by quark-antiquark ($q\bar{q}$) resonances. In the Resonance-Spectrum Expansion (RSE) [3], one may, in principle, ignore any specific dynamics of the $q\bar{q}$ system, since the RSE expressions only contain the resulting $q\bar{q}$ spectrum as input. Here, we will concentrate on the harmonic-oscillator approximation of the RSE (HORSE), for which the spectrum is equidistant with a level spacing of 380 MeV, independent of flavor.

It has almost become an automatism for experimental collaborations to interpret observed enhancements in scattering and production cross sections as resonances. On the other hand, most theorists compare the central masses of such enhancements to all sorts of model calculations, without even worrying how to reproduce the observed enhancements themselves. However, we have shown at different occasions that there exist at least four different types of enhancements, two of which are nonresonant and therefore should not be described by any kind of quark models that disregard decay thresholds. A careful study of both meson-meson data and the implications of our theory for scattering and production reveals that there exist enhancements which can be described by either *genuine* or *accidental resonances*, besides *threshold enhancements* and *depletion effects*.

Genuine resonances manifest themselves as poles in the scattering and production amplitudes, which are one-to-one related to $q\bar{q}$ states, or to possible other quark and/or gluonic configurations. This can be studied by gradually turning off the coupling between the confined $q\bar{q}$ channel(s) and the meson-meson channels in the scattering/production amplitudes. In this process, such poles end up at the positions corresponding to the real energy levels of the confinement states. [4, 5].

Accidental resonances are also designated by "dynamically generated resonances" in modern literature. They are generated solely by the coupling between $q\bar{q}$ and meson-meson channels. In the process of turning off the coupling, such poles disappear into the continuum, with ever increasing negative imaginary parts, thus becoming resonances with infinite widths [6].

Threshold enhancements occur in electron-positron annihilation reactions at the opening of new channels. In some cases these enhancements are large and allow for the discovery of genuine or accidental resonances in their tails [7], or even on top of the peaking structures [8]. Threshold enhancements themselves are nonresonating and do not correspond to poles in the scattering/production amplitudes.

Depletion effects may resemble somewhat enhancements but stem from a process of competition between decay channels, whereby genuine or accidental resonances as well as threshold enhancements in one channel deplete the signal in another channel [9]. In the channel of depleted signal, resonances and threshold enhancements are observed by dips instead of bumps in the cross sections, in contrast with what is observed in the other channel. The remaining structure, with the dips, may be be mistaken for a number of resonances between the dips, in many experimental and theoretical analyses.

In most approaches to strong interactions as well as light- and heavy-quark physics, the latter two types of enhancements cannot be described, as one is compelled to conclude from the countless model calculations outlined in Ref. [10], which, without exception, completely ignore the possibility of nonresonant enhancements.

The real $q\bar{q}$ resonances are often quite modest enhancements, and must be searched for with great care in experimental data. Recently, we have identified a few candidates for new vector charmonium states [7,9,11–13]. In Table 1 we compare these findings to the predictions from the pure HO spectrum (first column, "HORSE quenched"), which are given by

$$E_{q,n\ell} = 2m_q + \omega\left(2n+\ell+\frac{3}{2}\right) \quad , \tag{1}$$

for $q=c$, with the charm quark mass $m_c = 1.562$ GeV and oscillator frequency $\omega = 0.190$ GeV taken from Ref. [5]. The HORSE quenched nS and $(n-1)D$ $c\bar{c}$ masses are degenerate. We find

HORSE quenched	$\psi(D)$	$\psi(S)$
3.789	3.773 (1D [14])	3.686 (2S [14])
4.169	4.153 (2D [14])	4.039 (3S [14])
4.549	≈4.56 (3D [9,11])	4.421 (4S [14])
4.929	≈4.89 (4D [7,13])	≈4.81 (5S [7,13])
5.309	≈5.29 (5D [11])	≈5.13 (6S [11])
5.689	≈5.66 (6D [12])	≈5.44 (7S [12])
6.069	– (7D)	≈5.91 (8S [12])

Table 1: Central masses (GeV) of the higher vector charmonium states, including the well-known ones for three decades [14] and those extracted by us from data.

that the bare $c\bar{c}$ states turn into bound states below the $D\bar{D}$ threshold, or resonances thereabove, by unquenching the $c\bar{c}$ states through the insertion of open-charm meson-meson loops [3,4], also for bound states below the $D\bar{D}$ threshold. The S states (third column of Table 1) have central masses of about 100–200 MeV below the unquenched levels, whereas the D states (second column of Table 1) undergo much smaller mass shifts. The exact values of these mass shifts also depend on the specific positions of the open-charm thresholds with respect to the quenched $c\bar{c}$ states.

Results for beautonium alias bottomonium, taking $m_b = 4.724$ GeV [5] in Eq. (1) with $q = b$, are given in Table 2. We observe a $b\bar{b}$ spectrum which is very similar to the $c\bar{c}$ spectrum of Table 1, just shifted towards higher masses by about 6.3 GeV. However, our particle assignments are somewhat different from what one finds in most of the literature.

The experimental identification of the resonance at 10.845 GeV (CUSB) or 10.868 GeV (CLEO) and the resonance at 11.02 GeV (CUSB) or 11.019 GeV (CLEO) with the $\Upsilon(5S)$ and $\Upsilon(6S)$, respectively, was apparently inspired by the corresponding model predictions of Godfrey and Isgur [17], i.e., at 10.88 GeV and 11.10 GeV, respectively. However, we rather identify these resonances with the $\Upsilon(3D)$ and $\Upsilon(5S)$ states, respectively, on the basis of the level schemes in Tables 1 and 2 [4,5].

Z mesons

Matsuki, Morii, and Sudoh [18] were the first to suggest that the observed Z^+ resonances might

HORSE quenched	$\Upsilon(D)$	$\Upsilon(S)$
10.113	10.098 (1D [15])	10.023 (2S [14])
10.493	10.495 (2D [15])	10.355 (3S [14])
10.873	10.865 (3D [14])	10.735 (4S [16])
11.253	– (4D)	11.019 (5S [14])

Table 2: Energy levels (GeV) of the HORSE quenched $b\bar{b}$ spectrum; bound-state and central resonance masses (GeV) as deduced from experiment for the Υ vector states.

be higher excitations of the $D_s^*(2112)$ state. Now, since one indeed finds for the central masses of the $Z^+(4430)$ (alias $X(4430)^\pm$ [14]) and $Z^+(4050)$ (alias $X(4050)^\pm$ [14]) a mass difference of about 380 MeV, it is interesting to check the plausibility of the suggestion in Ref. [18]. If one takes a charm quark mass $m_c = 1.562$ GeV and a strange quark mass $m_s = 0.508$ GeV, as in Ref. [5], one obtains from Eq. (1) for the degenerate $\left(5\,{}^3D_1,\, 6\,{}^3S_1\right)$ pair a mass of 4.255 GeV, and for the degenerate $\left(6\,{}^3D_1,\, 7\,{}^3S_1\right)$ pair a mass of 4.635 GeV. This suggests that the $Z^+(4250)$ (alias $X(4250)^\pm$ [14]) could be the $D_s^*\left(5\,{}^3D_1\right)$. The $Z^+(4050)$ and the $Z^+(4430)$, with a mass shift of roughly 200 MeV due to meson loops, may then be identified with the $D_s^*\left(6\,{}^3S_1\right)$ and $D_s^*\left(7\,{}^3S_1\right)$, respectively.

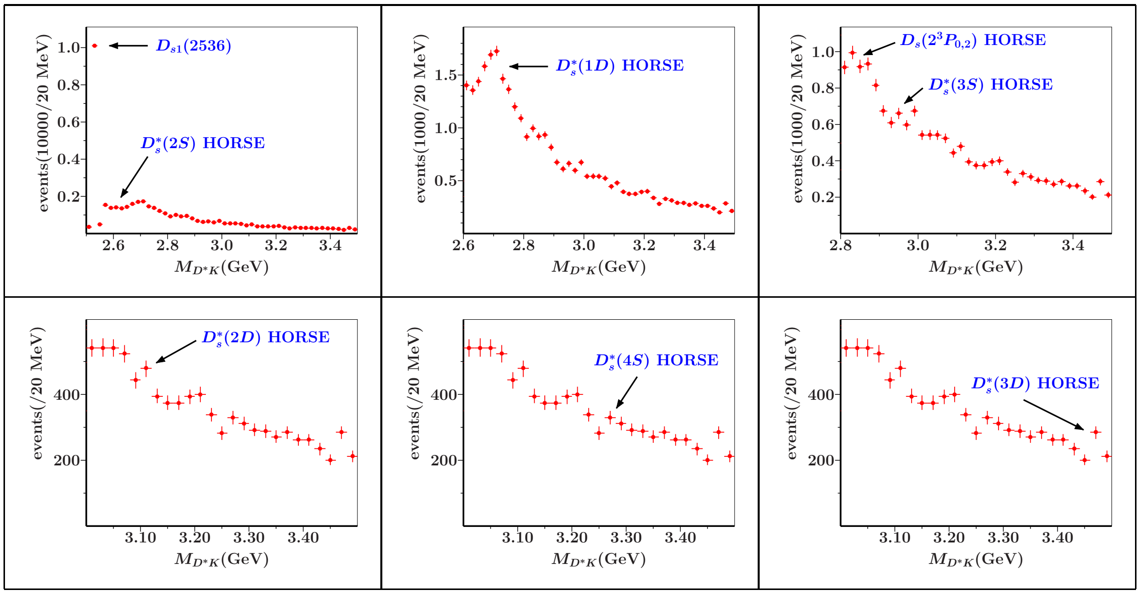

Figure 1: D^*K invariant-mass distribution from BABAR [19] and indications of possible D_s^* excitations.

Fortunately, we have at our disposal data on D^*K from BABAR [19], which is the channel where one expects to observe the higher excitations of the $D_s^*(2112)$. These data are displayed in Fig. 1. In the various plots here one can see structures in the data at approximately the energies for which the HORSE predicts D_s^* excitations. Consequently, the above suggestion is very well possible. We summarize our observations in Table 3. With respect to our $1D$ assignment for the $D_s^*(2.71)$, one must note the following. The $2S$ assignment by BABAR stems solely from branching ratios determined in Ref. [20]. If we calculate these branching ratios, using the coupling constants

states	HORSE quenched	observations
$1S$	2.355	$D_s^*(2.112)$ [14]
$2S$, $1D$	2.735	$2S$ difficult, $1D$: $D_s^*(2.71)$
$3S$, $2D$	3.115	$3S$ and $2D$ both possible
$4S$, $3D$	3.495	$4S$ and $3D$ both possible
$5S$, $4D$	3.875	–
$6S$, $5D$	4.255	$Z^+(4050)$ and $Z^+(4250)$
$7S$, $6D$	4.635	$Z^+(4430)$, $6D$ too high

Table 3: Energy levels (GeV) of the HORSE quenched $c\bar{s}$ spectrum; possible interpretation in terms of excited D_s^* or Z^+ resonances.

of Ref. [21], we find a ratio that is more than 3 times too large for the $2S$ state, and 77% of the experimental result for the $1D$. Moreover, since S and D states get mixed by meson loops, it is more likely to assume that the $D_s^*(2.71)$ is mainly $1D$. Unfortunately, the $D_s^*\left(2\,^3S_1\right)$ resonance is in the HORSE expected to be not far from the $D_{s1}(2536)$, and since the latter state produces a huge enhancement in the data, it may take quite some effort to find the $D_s^*\left(2\,^3S_1\right)$ in its vicinity.

A flavor-independent interference effect

In Refs. [22, 23] we described an interference effect that is visible in the cross sections of different annihilation processes. Although we have no explanation so far for such a phenomenon, it might add a second constant to the list of universal parameters for mesons.

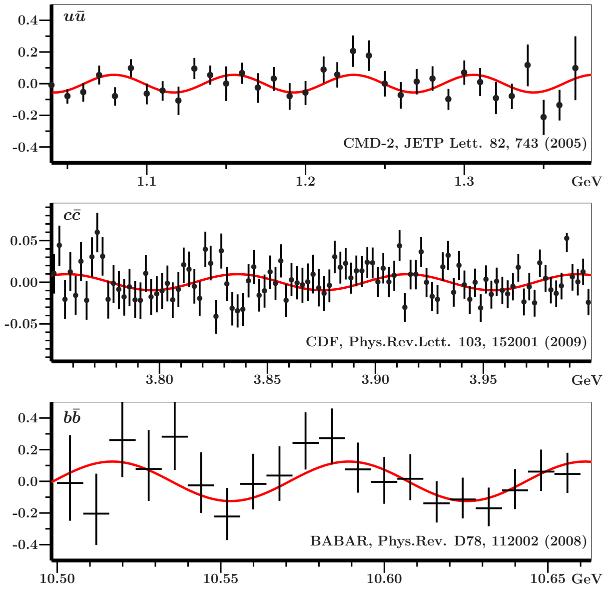

Figure 2: A flavor-independent interference effect is observed by us in data corresponding to processes for light quarks, $c\bar{c}$, and $b\bar{b}$ [23].

Summarizing, we have argued that a constant radial level splitting of about 380 MeV is consistent with light- and heavy-meson spectra. Furthermore, we presented a possible second flavor-independent observable for mesons. We also hinted at the possibility that the mysterious Z^+ resonances are just higher excitations in the D_s^* spectrum. Finally, we discussed ex-resonances that are either threshold enhancements or leftovers due to depletion effects.

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