The new resonances $Z_{cs}(3985)$ and $Z_{cs}(4003)$ (almost) fill two tetraquark nonets of broken SU(3)$_f$

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New data from BESIII and LHCb show the existence of resonances with strangeness filling multiplets of the broken SU(3)$_f$ symmetry, with the pattern predicted by the quark model. This is the case of the newly discovered $Z_{cs}(3985)$ and $Z_{cs}(4003)$, which have a natural accommodation in the tetraquark picture, as shown in this note. The quasi-degeneracy between $Z_{cs}(3985)$ and $Z_{cs}(4003)$ reproduces, in the strange sector, the situation observed with $X(3872)$ and $Z_c(3900)$. This represents a significative score in favor of the tetraquark scheme.

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Compact tetraquarks are hadrons made by diquark-antidiquark pairs held together by QCD forces in an overall color singlet. As stated in the original proposals and similarly to baryons and $q\bar{q}$ mesons, tetraquarks form complete multiplets of the flavour symmetry, SU(3)$_f$, broken by the light quark mass differences [11][13] (for reviews on exotic hadrons see [4][10]). Quark mass differences determine hadron mass differences in two ways: proportionally to the number of valence strange quarks and via the differences in hyperfine, spin-spin interaction, see [11–13].

Flavour SU(3)$_f$ multiplets are not expected for hypothetical hadronic molecular states, made by color singlet mesons and baryons bound together by forces mediated by color singlet particles. Similarly to what happens in nuclei and baryons see [4–10]. Quark mass differences determine hadron mass differences in two ways: proportionally to the number of valence strange quarks and via the differences in hyperfine, spin-spin interaction, see [11–13].

In this note we consider two hidden-charm, strange $J^P = 1^+$ resonances recently discovered, namely $Z_{cs}(3985)$, observed by the BESIII collaboration [14][15] in the reaction

$$e^+e^- \rightarrow K^+Z_{cs}^{-}(3985) \rightarrow K^+(D_s^-D^0 + D_s^-D^{*0})$$

(1)

and $Z_{cs}(4003)$ observed by the LHCb Collaboration in $B^+$ decay [16]

$$B^+ \rightarrow \phi + Z_{cs}(4003)^+ \rightarrow \phi + (K^+J/\psi)$$

(2)

We show that, together with well established $S$-wave tetraquarks, they fit neatly into two nonets of opposite charge conjugation.

The two particles in (1) and (2) have very different widths and are to be considered as two different states, in spite of being very close in mass. They reproduce in the strange sector the quasi-degeneracy between $X(3872)$ and $Z_c(3900)$ and can naturally be classified as the strange components of two $S$-wave tetraquark nonets: (i) a $J^{PC} = 1^{++}$ nonet associated with the $X(3872)$ and $X(4140)$; (ii) a $J^{PC} = 1^{+-}$ nonet associated with $Z_c(3900)$ [3] (see [4] and references therein).

The $S$-wave tetraquark structures we consider at the start have flavour and spin structures

$$X(3872) = [cq][\bar{c}\bar{q}], \ (J^{PC} = 1^{++}) : X = \frac{1}{\sqrt{2}}(|(1,0)_1) + |(0,1)_1|)$$

(3)

$$X(4140) = [cs][\bar{c}\bar{s}], \ (J^{PC} = 1^{++})$$

$$Z_{cs}(3900) = [cq][\bar{c}\bar{q}], \ (J^{PC} = 1^{+-}) : Z = \frac{1}{\sqrt{2}}(|(1,0)_1) - |(0,1)_1|)$$

(4)

$$Z_{cs}(4020) = [cq][\bar{c}\bar{q}], \ (J^{PC} = 1^{+-})$$

(5)

$q = u, d$, diquark and antidiquark spin are indicated and subscripts denote total spin. On the basis of its $J^{PC} = 1^{++}$ value, we include the $J/\psi$-$\phi$ resonance, $X(4140)$, as the $s\bar{s}$ component of the first nonet [3], a classification supported.
by the mass difference

\[ X(4140) - X(3872) = 275 \text{ MeV} \sim 2(m_s - m_u) \]  

(6)

To first order in SU(3)\textsubscript{flavor} breaking, the \( X(3872) \) nonet satisfies an equal spacing rule, and the assignment of \( X(3872) \) and \( X(4140) \) predicts the mass of the strange component to be:

\[ Z_{cs} = \frac{X(4140) + X(3872)}{2} = 4009 \text{ MeV} \]  

(7)

(we use particle mass values given by Particle Data Group [17]).

**Charge Conjugation for SU(3)\textsubscript{f} nonets.** A charge conjugation quantum number can be given to each self conjugate SU(3)\textsubscript{f} multiplet according to

\[ CTC = \eta_T \tilde{T} \]  

(8)

where \( C \) denotes the operator of charge conjugation, \( T \) the matrix representing the multiplet in SU(3) space and \( \tilde{T} \) the transpose matrix. \( \eta_T \) is the sign taken by neutral members, but it can be attributed to all members of the multiplet and is conserved in strong and electromagnetic decays, in the exact SU(3)\textsubscript{f} limit. \( \eta = -1 \) is given to the electromagnetic current \( J^\mu \) while \( \eta_{K,\pi} = +1 \).

Production and observed decays of \( Z_{cs}(3985) \) do not choose to which nonet \( Z_{cs}(3985) \) has to be assigned. An indication for \( Z_{cs}(4003) \) may come from the observed decay \( Z_{cs}(4003) \rightarrow K + J/\psi \), which, in the exact SU(3)\textsubscript{f} limit, points to the \( J^{PC} = 1^{+-} \) nonet, with the coupling required by invariance under transformation [8]

\[ \mathcal{M} = \lambda \mu \psi \text{Tr}\{Z, M\} = \lambda \mu \psi(Z_{cs}^+ K^- + \text{c.c.}) \]  

(9)

\( \lambda \) is an adimensional coupling, \( \mu \) has dimensions of a mass, \( Z \) and \( M \) are the matrices representing the \( J^{PC} = 1^{+-} \) tetraquark and meson nonets. However, the decay would also occur for the \( J^{PC} = 1^{++} \) nonet, to first order in SU(3)\textsubscript{f} symmetry breaking, with coupling

\[ \mathcal{M} = \lambda i \psi \text{Tr}(\epsilon_8[X, M]) \sim \lambda (m_s - m_u) i \psi(Z_{cs}^+ K^- - \text{c.c.}) \]  

(10)

with similar notations, \( \epsilon_8 = \text{diag}(m_u, m_d, m_s) \) the quark mass matrix and \( X \) the matrix representing the \( J^{PC} = 1^{++} \) nonet. In the following, we consider both possibilities.

**Solution 1.** The value in (7) is very close to the LHCb value in [16] so as to support the assignment of \( Z_{cs}(4003) \) to the \( J^{PC} = 1^{++} \) nonet, see Fig. 1. In this case, the \( Z_{cs} \) from BESIII belongs to the \( J^{PC} = 1^{+-} \) nonet and the equal spacing rule predicts its \( s\bar{s} \) component to the mass

\[ X_{s\bar{s}}(J^P = 1^{+-}) = 4076 \text{ MeV} \]  

(11)
In this solution, we find a spacing of 275 MeV in the $C = +1$ nonet, similar to $\rho - \phi$ spacing (244 MeV) and a spacing of 188 MeV for the $C = -1$ nonet, comparable to the spacing of tensor mesons $a_2(1320)$, $f_2^*(1525)$ (200 MeV), still in the range of the strange to light quark mass difference.

**Solution 2.** $Z_{cs}(3985)$ is associated to the $J^{PC} = 1^{++}$ nonet, with a disagreement of $\sim 27$ MeV with respect to the equal spacing rule. This is larger than the difference

$$K^*(892) - \frac{\phi(1020) + \rho(775)}{2} \sim 5 \text{ MeV}$$

that represents the violation of equal spacing rule in the vector meson nonet, but still acceptable. Associating $Z_{cs}(4003)$ to the $J^{PC} = 1^{+-}$ nonet, we predict

$$X_{ss}(J^{PC} = 1^{+-}) = 4121 \text{ MeV}. \quad (12)$$

In both solutions, one can anticipate that:

1. $Z_{cs}(4003)$ should appear also in process $[1]$ as a further peak in the $(D_s^- D^0 + D_s^- D^{*0})$ spectrum $[18]$;
2. $X_{ss}(J^P = 1^{+-})$ should be seen in the decay channels $\chi_c \phi$, $\bar{D}_s^* D_s$.

![Solution 2](image)

**FIG. 2:** Solution 2. Known and predicted tetraquarks for $C = +1$ and $C = -1$ nonets.

The discovery of two hidden charm-strange resonances, almost degenerate and in the right mass ballpark represents a remarkable progress towards the confirmation of the tetraquark scheme. Solution 1 is clearly more favourable, but Solution 2 cannot be excluded at the moment.

Besides confirming the $X_{ss}(J^{PC} = 1^{+-})$, much remains to be done. The shopping list towards complete nonets includes: a third $Z_{cs}$ with $J^P = 1^+$ for the nonet associated with $Z_c(4020)$, at an estimated mass of 4170 – 4200 MeV, a second $X_{ss}(J^{PC} = 1^{+-})$, the $I = 1$ partners of $X(3872)$, decaying into $J/\psi + \rho^\pm$ and the $I = 0$ partners of $Z_c(3900)$ and $Z_c(4020)$, possibly decaying into $J/\psi + f_0(500)$ (aka $\sigma$).

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$^1$ A particle heavier than $X(4140)$ with these quantum numbers and decay modes has been anticipated in [3].
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