New strange pentaquarks

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The new strange pentaquarks observed by LHCb are very likely hadronic molecules consisting of $\Xi_c \bar{D}$ and $\Xi_c \bar{D}^*$. We discuss the experimental evidence supporting this conclusion, pointing out the similarities and differences with the $P_c(4312)$, $P_c(4440)$ and $P_c(4457)$ pentaquarks in the nonstrange sector. The latter clearly are hadronic molecules consisting of $\Sigma_c \bar{D}$ and $\Sigma_c \bar{D}^*$. Following this line of thought, we predict three additional strange pentaquarks consisting of $\Xi'_c \bar{D}$ and $\Xi'_c \bar{D}^*$. The masses of these states are expected to be shifted upward by $M(\Xi'_c) - M(\Xi_c) \approx 110$ MeV with respect to the corresponding known strange pentaquarks.

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I. INTRODUCTION

Very recently the LHCb Collaboration announced observation of a new strange pentaquark $P^{\Lambda}_{\psi s}(4338)$[1] with minimal quark content $c\bar{c}uds$, mass $M = 4338.2 \pm 0.7$ MeV and width $\Gamma = 7.0 \pm 1.2$ MeV. This new state has been observed in the decay $B^- \to J/\psi \Lambda \bar{p}$ as a resonance in the $J/\psi\Lambda$ invariant mass with statistical significance $>10\sigma$. Amplitude analysis yields spin parity $J^P = 1/2^-$ with the alternative $J^P = 1/2^+$ rejected at 90% confidence level [1].

II. MOLECULAR INTERPRETATION

Several features of the new state are strongly suggestive [2] of a $\Xi_c \bar{D}$ hadronic molecule:

(a) Proximity to the relevant baryon-meson threshold. The central value of $P^{\Lambda}_{\psi s}(4338)$ mass is only 0.8 MeV above $\Xi_c^+ D^-$ threshold and 2.9 MeV above $\Xi_c^0 \bar{D}^0$ threshold (cf. Table I in the Appendix).

(b) Spin and parity. The spin and parity of an S-wave hadronic molecule are necessarily inherited from its constituents. In this case the latter are a positive parity spin-1/2 baryon and a negative parity spin-0 meson. $J^P = 1/2^-$ is exactly what is expected.

(c) Narrow width compared with the phase space available for decay. $P^{\Lambda}_{\psi s}(4338)$ decays into $J/\psi\Lambda$, whose threshold is 4212.6 MeV, so the Q-value is 126 MeV. The 7 MeV width of $P^{\Lambda}_{\psi s}(4338)$ is unnaturally small for such a Q-value, so there must be a suitable decay-suppressing mechanism at work. Decay into $J/\psi\Lambda$ requires the charmed and anticharmed quarks getting close to each other, but in a $\Xi_c \bar{D}$ molecular configuration the average distance between Ξ_c and $\bar{D}$ is much larger than 1 fm, automatically providing an efficient decay-suppressing mechanism.

Additional (although less statistically significant) support for the molecular interpretation is provided by earlier LHCb data on the $P^{\Lambda}_{\psi s}(4459)$ pentaquark [3,4]. In that case LHCb observed a strange pentaquark as a peak in $J/\psi\Lambda$ invariant mass in the decay $\Xi_b^- \to J/\psi \Lambda K^-$, with mass $M = 4458.8 \pm 2.9^{+4.7}_{-1.1}$ MeV, width $\Gamma = 17.3 \pm 6.5^{+8.0}_{-5.7}$ MeV and statistical significance of 3.1σ. The central value of the $P^{\Lambda}_{\psi s}(4459)$ mass is approximately 20 MeV below the $\Xi_c \bar{D}^*$ threshold.

Remarkably, LHCb observed [3] that this resonance can equally well be described by a two-peak structure, with the two peaks split by 13 MeV:

$$P^{\Lambda}_{\psi s}(4455){:}\ M = 4454.9 \pm 2.7\ \text{MeV}, \quad \Gamma = 7.5 \pm 9.7\ \text{MeV},$$
$$P^{\Lambda}_{\psi s}(4468){:}\ M = 4467.8 \pm 3.7\ \text{MeV}, \quad \Gamma = 5.2 \pm 5.3\ \text{MeV}. \tag{1}$$

This pattern is consistent with general expectations (see, e.g., Refs. [5–8]). For a recent review and additional references, see Ref. [9].

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[1]We employ here a new naming scheme suggested by LHCb. An alternative name for this state is $P_{cs}(4338)$.

The above structure is highly reminiscent of the two-peak pentaquark structure discovered by LHCb [10] in the nonstrange sector, following the original discovery of hidden-charm pentaquarks [11],

$$P_\psi^N(4440)^+:\ M = 4440.3 \pm 1.3^{+4.1}_{-4.7}\ \text{MeV}, \qquad \Gamma = 20.6 \pm 4.9^{+8.7}_{-10.1}\ \text{MeV},$$
$$P_\psi^N(4457)^+:\ M = 4457.3 \pm 0.6^{+4.1}_{-1.7}\ \text{MeV}, \qquad \Gamma = 6.4 \pm 2.0^{+5.7}_{-1.9}\ \text{MeV}$$
$$[\text{also known as } P_c(4440)^+ \text{ and } P_c(4457)^+]. \tag{2}$$

These two resonances are most likely the two possible spin states of an S-wave hadronic molecule consisting of a spin-1/2 Σ_c and spin-1 $\bar{D}^*$. Clearly, in that case the expected J^P values are $1/2^-$ and $3/2^-$.

Analogous reasoning leads to the expectation that the spin and parity of $P_{\psi s}^\Lambda(4455)$ and $P_{\psi s}^\Lambda(4468)$ are the two possible values for an S-wave hadronic molecule consisting of a spin-1/2 Ξ_c and spin-1 $\bar{D}^*$, i.e. $1/2^-$ and $3/2^-$.

In view of the above it is natural to interpret $P_{\psi s}^\Lambda(4338)$ as the strange analog of $P_\psi^N(4312)^+$ also reported in [10], with $M = 4311.9 \pm 0.7^{+6.8}_{-0.6}$ MeV and $\Gamma = 9.8 \pm 2.7^{+3.7}_{-4.5}$ MeV, commonly interpreted as a $\Sigma_c \bar{D}$ hadronic molecule.

III. BINDING MECHANISMS

One remaining issue is the specific mechanism which provides attraction between $\bar{D}$ and Ξ_c. Binding between $\bar{D}^*$ and Σ_c or Ξ_c can be provided by one-pion exchange. But since $\bar{D}$ is a pseudoscalar, its binding to another hadron cannot be provided by one-pion exchange, because that would require a vertex involving three pseudoscalars which is forbidden in QCD, since such a vertex cannot simultaneously conserve parity and angular momentum.

In the case of a $\Sigma_c \bar{D}$ hadronic molecule a two-pion exchange can provide binding, because the intermediate $\Lambda_c \bar{D}^*$ state is relatively close in mass to the initial state [12]. Two-pion exchange is expected to be weaker than one-pion exchange and as a result $P_\psi^N(4312)^+$ might be a virtual state, rather than a fully fledged bound state.

For $\Xi_c \bar{D}$ two-pion exchange is unlikely to work, since in this case the intermediate state is too heavy. One relatively simple possibility is ρ-mediated t-channel charge exchange,

$$\Xi_c^0 \bar{D}^0 \underset{\rho^-}{\longrightarrow} \Xi_c^+ D^-, \qquad \Xi_c^+ \bar{D}^- \underset{\rho^+}{\longrightarrow} \Xi_c^0 \bar{D}^0. \tag{3}$$

The $\Xi_c \bar{D}$ state decays into $\Lambda J/\psi$, so it has isospin zero. In such a state t-channel ρ exchange is attractive [13]. Clearly, more quantitative statements require specific model-dependent calculations, as in (e.g.,) Refs. [14,15].

IV. MOLECULES WITH Ξ_c'

At this point it is important to stress that the analogy between $\Sigma_c \bar{D}^{(*)}$ and $\Xi_c \bar{D}^{(*)}$ hadronic molecules goes only so far. As discussed in Ref. [4], $P_{\psi s}^\Lambda(4455)$ and $P_{\psi s}^\Lambda(4468)$ do not correspond to an $SU(3)_F$ rotation $q \to s$ ($q = u, d$) of $P_\psi^N(4440)^+$ and $P_\psi^N(4457)^+$, nor does $P_{\psi s}^\Lambda(4338)$ correspond to an $SU(3)_F$ rotation of $P_\psi^N(4312)^+$.

The point is that in the nonstrange pentaquark hadronic molecules the charmed baryon is Σ_c, in which the two light quarks form a "bad diquark" (ud), with spin-1 and isospin-1. An $SU(3)_F$ rotation $q \to s$ then takes the Σ_c baryon to Ξ_c', rather than to Ξ_c. The latter is approximately 110 MeV lighter than Ξ',[2] because in Ξ_c the light quarks form a spin-0 $[qs]$ "good diquark" which is significantly lighter than the spin-1 qs bad diquark in Ξ_c'.

Moreover, Ξ_c' cannot decay via the strong interaction, because $M(\Xi_c') - M(\Xi_c) < m_\pi$. It can only decay radiatively, $M(\Xi_c') \to M(\Xi_c)\gamma$. Thus from the point of view of strong interactions Ξ_c' is as stable as Ξ_c.

The upshot of the above observations is that, if—as strongly hinted by the data—$P_{\psi s}^\Lambda(4338)$, $P_{\psi s}^\Lambda(4455)$ and $P_{\psi s}^\Lambda(4468)$ indeed are $\Xi_c \bar{D}$ and $\Xi_c \bar{D}^*$ hadronic molecules, then one should expect analogously three additional narrow strange pentaquarks corresponding to $\Xi_c' \bar{D}$ and $\Xi_c' \bar{D}^*$ hadronic molecules. Their masses are expected to be shifted by $M(\Xi_c') - M(\Xi_c) \approx 110$ MeV with respect to the corresponding known strange pentaquarks, putting them approximately at 4448, 4564 and 4577 MeV, as shown in Fig. 1. Their spin-parity quantum numbers are expected to be the same as those of their counterparts. Their widths are expected to be rather small, similar to those of $P_{\psi s}^\Lambda(4338)$, $P_{\psi s}^\Lambda(4455)$ and $P_{\psi s}^\Lambda(4468)$.

A potentially challenging point is that the $\Xi_c' \bar{D}$ state at 4448 MeV, analogous to $P_{\psi s}^\Lambda(4338)$, is expected just 7 MeV below $P_{\psi s}^\Lambda(4455)$. This is because $\bar{D}^* - \bar{D}$ splitting, plus the $\Xi_c \bar{D}^*$ binding energy is close to $\Xi_c' - \Xi_c$ splitting. $\Xi_c' \bar{D}$ state is expected to have spin-1/2, so if $P_{\psi s}^\Lambda(4455)$ turns out to also have spin-1/2, the two states will likely mix.

[2] $M(\Xi_c'^+) - M(\Xi_c^+) = 110.5 \pm 0.4$ MeV and $M(\Xi_c'^0) - M(\Xi_c^0) = 108.3 \pm 0.4$ MeV; cf. the Appendix.

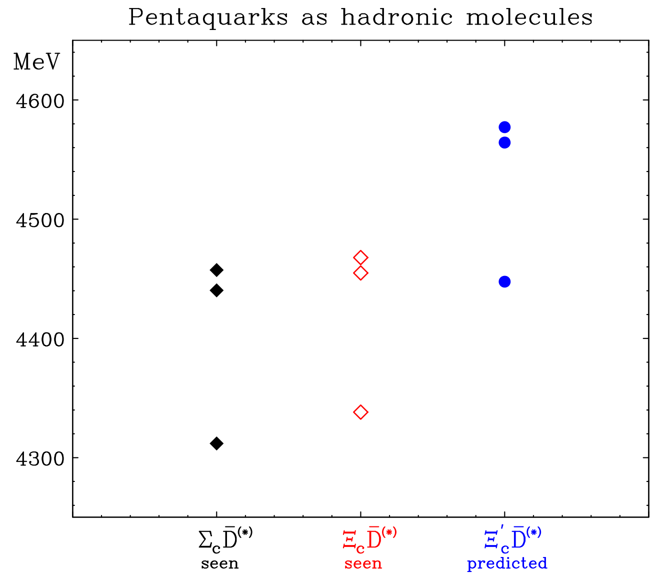

FIG. 1. Pentaquarks as hadronic molecules. $\Sigma_c\bar{D}^{(*)}$ states are denoted by black diamonds, $\Xi_c\bar{D}^{(*)}$ states by open red diamonds and $\Xi'_c\bar{D}^{(*)}$ states by blue circles.

V. SUMMARY

Recently LHCb has reported several new narrow strange pentaquarks decaying into $\Lambda J/\psi$, with minimal quark content $c\bar{c}uds$. We have reviewed the experimental evidence and theoretical arguments strongly suggesting that they are $\Xi_c\bar{D}^{(*)}$ hadronic molecules. The main points are their proximity to the relevant baryon-meson thresholds, spin parity and unnaturally narrow widths, given the phase space available for decay.

We have discussed their similarities and differences with the three nonstrange narrow pentaquarks decaying into pJ/ψ, with minimal quark content $c\bar{c}uud$ reported by LHCb in 2019.

On the basis of this discussion, we have predicted three additional narrow strange pentaquarks, corresponding to $\Xi'_c\bar{D}^{(*)}$ hadronic molecules, with masses shifted upward by approximately 110 MeV with respect to the known $\Xi_c\bar{D}^{(*)}$ states, i.e., approximately at 4448, 4564 and 4557 MeV and narrow widths.

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APPENDIX: CHARMED HADRON MASSES

TABLE I. Masses of charmed hadrons discussed in the text.

State	Mass (MeV) [16]
Σ_c^+	$2452.65^{+0.22}_{-0.16}$
Σ_c^0	$2453.75^{+0.14}_{-0.14}$
Ξ_c^+	$2467.71^{+0.23}_{-0.23}$
Ξ_c^0	$2470.44^{+0.28}_{-0.28}$
$\Xi_c'^+$	$2578.2^{+0.5}_{-0.5}$
$\Xi_c'^0$	$2578.7^{+0.5}_{-0.5}$
$\bar{D}^0$	$1864.84^{+0.05}_{-0.05}$
D^-	$1869.66^{+0.05}_{-0.05}$
$\bar{D}^{*0}$	$2006.85^{+0.05}_{-0.05}$
D^{*-}	$2010.26^{+0.05}_{-0.05}$

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