New strange pentaquarks

Marek Karliner and Jonathan L. Rosner

a School of Physics and Astronomy
Raymond and Beverly Sackler Faculty of Exact Sciences
Tel Aviv University, Tel Aviv 69978, Israel

b Enrico Fermi Institute and Department of Physics
University of Chicago, 5620 S. Ellis Avenue, Chicago, IL 60637, USA

ABSTRACT

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 non-strange 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 upwards by $M(\Xi'_c) - M(\Xi_c) \approx 110$ MeV with respect to the corresponding known strange pentaquarks.

Very recently the LHCb Collaboration announced observation of a new strange pentaquark $P_{cs}^A(4338)$ 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 @90% confidence level [1].

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

(a) Vicinity to the relevant baryon-meson threshold. The central value of $P_{cs}^A(4338)$ mass is only 0.8 MeV above $\Xi_c^+ D^-$ threshold and 2.9 MeV above $\Xi_c^0 D^0$ threshold (cf. Appendix A).

(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.

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1 marek@tauex.tau.ac.il
2 rosner@hep.uchicago.edu
3 We employ here a new naming scheme suggested by LHCb. An alternative name for this state is $P_{cs}(4338)$. 

15 Jul 2022
(c) Narrow width, compared with the phase space available for decay. $P_{\psi s}^\Lambda(4338)$ decays into $J/\psi \Lambda$, whose threshold is 4212.6 MeV, so the $Q$-value is 126 MeV. The 7 MeV width of $P_{\psi s}^\Lambda(4338)$ 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 anti-charmed quarks getting close to each other, but in a $\Xi_c \bar{D}$ molecular configuration the average distance between $\Xi_c$ and $\bar{D}$ is much larger than 1 fermi, 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 $P_{\psi s}^\Lambda(4459)$ pentaquark \cite{3,4}. In that case LHCb observed a strange pentaquark as a peak in $J/\psi \Lambda$ invariant mass in the decay $\Xi_c^{-} \to J/\psi \Lambda K^-$, with mass $M = 4458.8 \pm 2.9_{-1.1}^{+4.7}$ MeV, width $\Gamma = 17.3 \pm 6.5_{-5.7}^{+8.0}$ MeV and statistical significance of 3.1 $\sigma$. The central value of the $P_{\psi s}^\Lambda(4459)$ mass is approximately 20 MeV below the $\Xi_c \bar{D}$ threshold.

Remarkably, LHCb observed \cite{3} that this resonance can equally well be described by a two peak structure, with the two peaks split by 13 MeV:

$$P_{\psi s}^\Lambda(4455) : \quad M = 4454.9 \pm 2.7 \text{ MeV}, \quad \Gamma = 7.5 \pm 9.7 \text{ MeV}$$

$$P_{\psi s}^\Lambda(4468) : \quad M = 4467.8 \pm 3.7 \text{ MeV}, \quad \Gamma = 5.2 \pm 5.3 \text{ MeV}. \quad (1)$$

This pattern is consistent with general expectations (see, e.g., Refs. \cite{7,10}). For a recent review and additional references, see Ref. \cite{11}.

The above structure is highly reminiscent of the two-peak pentaquark structure discovered by LHCb \cite{5} in the non-strange sector, following the original discovery of hidden-charm pentaquarks \cite{6},

$$P_{\psi}^N(4440)^+ : \quad M = 4440.3 \pm 1.3_{-4.1}^{+4.4} \text{ MeV}, \quad \Gamma = 20.6 \pm 4.9_{-10.1}^{+8.7} \text{ MeV}$$

$$P_{\psi}^N(4457)^+ : \quad M = 4457.3 \pm 0.6_{-1.7}^{+4.1} \text{ MeV}, \quad \Gamma = 6.4 \pm 2.0_{-1.9}^{+5.7} \text{ MeV}. \quad (2)$$

(a.k.a. $P_c(4440)^+$ and $P_c(4457)^+$)

These two resonances are most likely the two possible spin states of an $S$-wave hadronic molecule consisting of a spin-1/2 $\Sigma_c$ 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 $\Sigma_c$ 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 analogue of $P_{\psi}^N(4312)^+$ also reported in \cite{5}, with $M = 4311.9 \pm 0.7_{-0.6}^{+6.8}$ MeV and $\Gamma = 9.8 \pm 2.7_{-1.4}^{+3.7}$ MeV, commonly interpreted as a $\Sigma_c \bar{D}$ hadronic molecule.

One remaining issue is the specific mechanism which provides attraction between $\bar{D}$ and $\Xi_c$. Binding between $\bar{D}$ and $\Sigma_c$ or $\Xi_c$ 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 $\Xi_c^0$. Two-pion exchange is expected to be weaker than one-pion exchange and as a result $P_{\psi^s}^{\Lambda}(4312)^+$ 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 $\rho$-mediated $t$-channel charge exchange,

$$\Xi^0_c \bar{D}^0 \rightarrow \rho^- \Xi^+_c \bar{D}^- \quad \Xi^+_c \bar{D}^- \rightarrow \rho^+ \Xi^0_c \bar{D}^0$$  \hspace{1cm} (3)

The $\Xi_c \bar{D}$ state decays into $\Lambda J/\psi$, so it has isospin zero. In such a state $t$-channel $\rho$ exchange is attractive $[13]$. Clearly, more quantitative statements require a specific model-dependent calculation.

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 $q \rightarrow s$ ($q = u,d$) of $P_{\psi}^{\Sigma}(4440)^+$ and $P_{\psi}^N(4457)^+$. Neither does $P_{\psi^s}^{\Lambda}(4338)$ correspond to an $SU(3)_F$ rotation of $P_{\psi}^N(4312)^+$.

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

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

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.

**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

$^M(\Xi^+ c) - M(\Xi^+ D) = 110.5 \pm 0.4$ MeV and $M(\Xi^0_c) - M(\Xi^0 D) = 108.3 \pm 0.4$ MeV, cf. Appendix.
Figure 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.

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 $pJ/\psi$, with minimal quark content $c\bar c u u d$, reported by LHCb in 2019.

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

ACKNOWLEDGMENTS

The research of M.K. was supported in part by NSFC-ISF grant No. 3423/19.
APPENDIX

| state   | mass (MeV) |
|---------|------------|
| $\Sigma_c^+$ | 2452.65$^{+0.22}_{-0.16}$ |
| $\Sigma_c^0$  | 2453.75$^{+0.14}_{-0.14}$ |
| $\Xi_c^+$     | 2467.71$^{+0.23}_{-0.23}$ |
| $\Xi_c^0$     | 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$^{+0.05}_{-0.05}$ |
| $\bar{D}^*$  | 2006.85$^{+0.05}_{-0.05}$ |
| $D^{**}$     | 2010.26$^{+0.05}_{-0.05}$ |

Table I: Masses of charmed hadrons discussed in the text.

References

[1] LHC seminar “Particle Zoo 2.0: New tetra- and pentaquarks at LHCb”, July 5, 2022, https://indico.cern.ch/event/1176505/ and LHCb-PAPER-2022-031, in preparation.

[2] M. Karliner and J. L. Rosner, “New Exotic Meson and Baryon Resonances from Doubly-Heavy Hadronic Molecules”, Phys. Rev. Lett. 115, 122001 (2015) [arXiv:1506.06386 [hep-ph]].

[3] R. Aaij et al. [LHCb], “Evidence of a $J/\psi \Lambda$ structure and observation of excited $\Xi^-$ states in the $\Xi_b^- \to J/\psi \Lambda K^-$ decay,” Sci. Bull. 66, 1278 (2021) [arXiv:2012.10380 [hep-ex]].

[4] M. Karliner and J. L. Rosner, “Strange pentaquarks and excited $\Xi$ hyperons in $\Xi_b^- \to J/\psi \Lambda K^-$ final states”, Sci. Bull. 66, 1256 (2021) [arXiv:2104.15077 [hep-ph]].

[5] R. Aaij et al. [LHCb], “Observation of a narrow pentaquark state, $P_c(4312)^+$, and of two-peak structure of the $P_c(4450)^+$”, Phys. Rev. Lett. 122, 222001 (2019) [arXiv:1904.03947 [hep-ex]].

[6] R. Aaij et al. [LHCb], “Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays”, Phys. Rev. Lett. 115, 072001 (2015) [arXiv:1507.03414 [hep-ex]].

[7] J. J. Wu, R. Molina, E. Oset and B. S. Zou, “Prediction of narrow $N^*$ and $\Lambda^*$ resonances with hidden charm above 4 GeV”, Phys. Rev. Lett. 105, 232001 (2010) [arXiv:1007.0573 [nucl-th]].
[8] R. Chen, J. He and X. Liu, “Possible strange hidden-charm pentaquarks from $\Sigma_c^{(*)}D_s^{(*)}$ and $\Xi_c^{(*)}D_s^{(*)}$ interactions”, Chin. Phys. C 41, no.10, 103105 (2017) [arXiv:1609.03235 [hep-ph]].

[9] C. W. Shen, J. J. Wu and B. S. Zou, “Decay behaviors of possible $\Lambda_{c\bar{c}}$ states in hadronic molecule pictures”, Phys. Rev. D 100, 056006 (2019) [arXiv:1906.03896 [hep-ph]].

[10] B. Wang, L. Meng and S. L. Zhu, “Spectrum of the strange hidden charm molecular pentaquarks in chiral effective field theory”, Phys. Rev. D 101, 034018 (2020) [arXiv:1912.12592 [hep-ph]].

[11] X. K. Dong, F. K. Guo and B. S. Zou, “A survey of heavy-heavy hadronic molecules”, Commun. Theor. Phys. 73, no.12, 125201 (2021) [arXiv:2108.02673 [hep-ph]].

[12] M. Karliner, Hidden Charm Molecular Pentaquarks: Some Open Questions, Bled Workshops in Physics 20, 15 (2019), [http://www-f1.ijs.si/BledPub/bled2019.pdf]

[13] F. Q. Wu and B. S. Zou, “Role of $t$-channel meson exchange in $S$-wave $\pi N$ and $K N$ scattering”, Chin. Phys. C 32, 629 (2008) [arXiv:0710.5855 [hep-ph]].

[14] R.L. Workman et al. [Particle Data Group], “Review of Particle Physics”, to be published in Prog. Theor. Exp. Phys. 2022, 083C01 (2022), also online at https://pdg.lbl.gov/.