Double-Strangeness Molecular-Type Pentaquarks from Coupled-Channel Dynamics

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The existence of pentaquarks with strangeness content zero and one are major discoveries of the latest years in hadron physics. Most of these states can be understood as hadronic molecules and were predicted prior to their discovery within a model based on unitarized meson-baryon amplitudes obtained from vector-meson exchange interactions. Contrary to earlier statements, we show this model to also predict the existence of pentaquarks with double strangeness, at about 4500 and 4600 MeV, which are generated in a very specific and unique mechanism, via an attraction induced by a strong coupling between the two heaviest meson-baryon states.

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Introduction.—Since the turn of the millennium, an increasing amount of data obtained by several collaborations (Belle, *BABAR*, LHCb, and BESII) has produced many exotic hadrons which appear to be inconsistent with the predictions of the conventional quark model [1,2]. The discovery at LHCb [3,4] of excited nucleon resonances [$P^N_{\Psi_s}(4312)$, $P^N_{\Psi_s}(4440)$, and $P^N_{\Psi_s}(4457)$], seen on the invariant mass distribution of $J/\Psi p$ pairs from the decay $\Lambda_b \to J/\Psi p K^-$, has been the first clear evidence of the existence of pentaquark baryons, as a $c\bar{c}$ pair is necessary to explain their high mass. In a later experiment [5], the $J/\Psi\Lambda$ spectrum, obtained from the decay $\Xi_b^- \to J/\Psi\Lambda K^-$, also provided evidence for a pentaquark, the $P^\Lambda_{\Psi_s}(4459)$, this time with one unit of strangeness content. More recently, an analysis of the $B^- \to J/\Psi\Lambda\bar{p}$ decay points at the existence of another narrow hidden-charm pentaquark with strangeness, the $P^\Lambda_{\Psi_s}(4338)$ [6].

Among the various theoretical interpretations on the nature of these pentaquarks, the possibility that they could be structured as meson-baryon molecules was already predicted in Refs. [7–9], prior to their discovery, and has gained interest ever since due to their proximity to various charmed meson-baryon thresholds (see Refs. [10,11], and references therein). Many of these studies assume a t-channel vector-meson exchange interaction between mesons and baryons, which is unitarized in coupled channels. However, a hidden-charm pentaquark with double strangeness was not found in this approach [8,9]. From a hadronic molecular perspective, it is interesting to note that the usually adopted alternative of molecular binding through a long-range interaction mediated by the exchange of pions between the constituent hadrons is not possible in the heavy part of strangeness $S = -2$ sector. In fact, a (no-pion) light meson exchange model [12] finds doubly strange hidden-charm pentaquarks but requiring a unrealistically large regularization cutoff parameter. Let us finally mention that recent studies relying on the quark substructure of the state also predict double-strangeness pentaquark candidates [13–15].

The unitarized coupled-channel hidden gauge formalism has been a very successful approach in explaining other exotic hadrons first in the strange and later in the charm and hidden-charm sectors (see Ref. [16] and references therein). The most known example is the $\Lambda(1405)$ resonance, whose mass was systematically predicted to be too high by quark models, but it found a better explanation as a resonant structure from a coupled-channel $\bar{K}N$ interaction. This picture, which would consolidate the $\Lambda(1405)$ as the first pentaquark ever, finds support in its predicted double-pole nature [17,18], confirmed later from the different line shapes observed [19] and now commonly accepted in the field [20].

In this Letter, we revisit the unitarized coupled-channel approach [8,9] and demonstrate that, within realistic model parameters, it does predict the existence of strangeness $S = -2$ pentaquarks in a very unique way, namely, via an attraction generated by a strong coupling between the two heaviest meson-baryon channels. This finding not only complements the family of $S = 0$, and $S = -1$ pentaquarks obtained within the same formalism, but, if confirmed experimentally, it would strongly support the validity of the unitarized t-channel vector-meson exchange interaction models in explaining hadron molecules, as the alternative pion-exchange mechanism is forbidden in this sector.

Formalism.—The model employed in this Letter relies on a meson-baryon interaction in the S wave, which is built up from the t-channel diagram in Fig. 1, where the mesons are depicted by dashed lines and the baryons by solid lines. The external mesons in the diagram represent the ground states of either pseudoscalar $[J^P(M) = 0^-]$ or vector $[J^P(M) = 1^-]$ type, while the baryons are the lowest-energy ones with $J^P(B) = 1/2^+$, all of them composed out of u, d, s, and c quarks and antiquarks. The indices i and j label the different meson-baryon channels with the same spin parity (J^P), isospin, and flavor quantum numbers that can be connected by the exchange of a vector meson V^*.

The VPP (VVV) and VBB vertices in the diagram are described by effective Lagrangians which are obtained using the local hidden gauge formalism [21,22] and assuming SU(4) symmetry:

$$\mathcal{L}_{VPP} = -ig\langle[\phi, \partial_\mu \phi]V^\mu\rangle,$$
$$\mathcal{L}_{VBB} = \frac{g}{2}\sum_{i,j,k,l=1}^{4} \bar{B}_{ijk}\gamma^\mu (V^k_{\mu,l}B^{ijl} + 2V^j_{\mu,l}B^{ilk}),$$
$$\mathcal{L}_{VVV} = ig\langle[V^\mu, \partial_\nu V_\mu]V^\nu\rangle, \tag{1}$$

where ϕ and V_μ represent the 16-plet of pseudoscalar and vector fields, respectively, $\langle\rangle$ denotes the trace in SU(4) flavor space, and $g = m_V/2f$ is the universal coupling constant, related to the pion decay constant ($f = 93$ MeV) via a characteristic mass of the light uncharmed vector meson from the nonet (m_V).

Using the VPP and VBB Lagrangians of Eq. (1), one can obtain the interaction of pseudoscalar mesons with baryons, referred to as PB interaction from now on. In the limit where the mass of the exchanged meson is much bigger than its four-momentum, the t-channel diagram in Fig. 1 reduces to a contact term, and, up to $\mathcal{O}(p^2/M^2)$, its S-wave expression reads

$$V_{ij}(\sqrt{s}) = -C_{ij}\frac{1}{4f^2}(2\sqrt{s} - M_i - M_j)N_i N_j, \tag{2}$$

where N_i and N_j are normalization factors, $N_i = \sqrt{(E_i + M_i)/2M_i}$, and M_i (E_i) and M_j (E_j) are the mass (energy) of the baryon in the incoming and outgoing channels, respectively. The coefficients C_{ij} contain the SU(4) Clebsch-Gordan factors encoded in the Lagrangians in Eq. (1), as well as the ratio between m_V^2 and the mass squared of the vector meson exchanged which, in the SU(4) limit, is also m_V^2. However, the transitions studied here involve the exchange of vector mesons with quite different masses, and this is taken into account as follows. The mass of all the light vector mesons, composed out of u, d, and s quarks and their corresponding antiquarks, is assumed to be the same as and equal to m_V. The mass of mesons with one charm or anticharm quark is assumed to be roughly twice that of the uncharmed ones; hence, the coefficients tied to their exchange will carry a factor $\kappa_c = (m_V/m_V^c)^2 \simeq 1/4$. Finally, the mass of the J/Ψ meson is taken to be 3 times that of the light ones, so that the terms induced by its exchange carry a factor $\kappa_{cc} \simeq 1/9$ in this case.

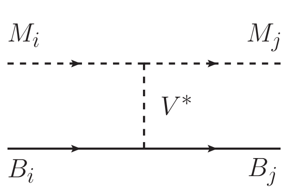

FIG. 1. Leading-order tree-level diagram contributing to the meson-baryon interaction. Baryons and mesons are depicted by solid and dashed lines, respectively.

In the present Letter, we focus on the isospin $I = 1/2$ and strangeness $S = -2$ sector of the pentaquark, which can be realized by nine possible combinations of a pseudoscalar meson and a baryon, namely, $\pi\Xi(1456)$, $\bar{K}\Lambda(1611)$, $\bar{K}\Sigma(1689)$, $\eta\Xi(1866)$, $\eta'\Xi(2276)$, $\eta_c\Xi(4298)$, $\bar{D}_s\Xi_c(4437)$, $\bar{D}_s\Xi'_c(4545)$, and $\bar{D}\Omega(4565)$, where the values in parentheses indicate their thresholds in MeV. As the mass of the four channels with charm quarks is more than 2 GeV larger than that of the other channels, we can then expect these two energy regions to behave independently and the corresponding channels to have a small influence on each other. Hence, we consider only the four heavy channels and present the corresponding values of the C_{ij} coefficients in Table I.

Similarly, using the VVV and VBB Lagrangians in Eq. (1), one can obtain the interaction of vector mesons with baryons, referred to as the VB interaction from now on. Neglecting the momentum of the external vector mesons versus their mass, their polarization vectors become essentially spatial, and the resulting VB interaction kernel is then identical to that for the interaction of pseudoscalar mesons with baryons [Eq. (2)] but multiplied by the scalar product $\vec{\epsilon}_i \cdot \vec{\epsilon}_j$.

In the VB interaction case, the allowed channels are $\rho\Xi(2089)$, $\bar{K}^*\Lambda(2010)$, $\bar{K}^*\Sigma(2087)$, $\omega\Xi(2101)$, $\phi\Xi(2338)$, $J/\Psi\Xi(4415)$, $\bar{D}_s^*\Xi_c(4581)$, $\bar{D}_s^*\Xi'_c(4689)$, and $\bar{D}^*\Omega(4706)$, where again we can separate the channels in two energy regions. Focusing on the heavy channels, the matrix of C_{ij}

TABLE I. C_{ij} coefficients of the PB the interaction in the $(I, S) = (1/2, -2)$ sector.

	$\eta_c\Xi$	$\bar{D}_s\Xi_c$	$\bar{D}_s\Xi'_c$	$\bar{D}\Omega_c$
$\eta_c\Xi$	0	$\sqrt{\frac{3}{2}}\kappa_c$	$\frac{1}{\sqrt{2}}\kappa_c$	$-\kappa_c$
$\bar{D}_s\Xi_c$		$-1+\kappa_{cc}$	0	0
$\bar{D}_s\Xi'_c$			$-1+\kappa_{cc}$	$\sqrt{2}$
$\bar{D}\Omega_c$				κ_{cc}

coefficients is identical to that in Table I with the following replacements in the labeling: $\eta_c \to J/\Psi$, $\bar{D} \to \bar{D}^*$, and $\bar{D}_s \to \bar{D}_s^*$.

The sought resonances are dynamically generated as poles of a properly unitarized scattering amplitude T_{ij}. We employ the Bethe-Salpeter equation in coupled channels, which implements a resummation of meson-baryon loops, denoted by G_l, to infinite order:

$$T_{ij} = V_{ij} + V_{il} G_l T_{lj}. \quad (3)$$

Note that, in the case of the VB amplitude, the sum over the polarization of the internal vector meson gives $\sum_{\rm pol} \epsilon_i \epsilon_j = \delta_{ij} + (q_i q_j / M_V^2)$ but, consistently with our model, the q^2/M_V^2 term is neglected, and this permits factorizing a factor $\vec{\epsilon}_i \vec{\epsilon}_j$ out from all terms in the Bethe-Salpeter equation. By adopting the commonly employed approximation of factorizing the V and T on-shell amplitudes out of the intermediate integrals, the above integral equation reduces to a simple algebraic one: $T = (1 - VG)^{-1} V$, where G is a diagonal matrix containing the meson-baryon loop functions given by

$$G_l(P) = i \int \frac{d^4 q}{(2\pi)^4} \frac{2M_l}{(P-q)^2 - M_l^2 + i\epsilon} \frac{1}{q^2 - m_l^2 + i\epsilon}, \quad (4)$$

M_l and m_l denoting the mass of the baryon and meson in the loop, respectively, $P = p + k = (\sqrt{s}, 0)$ being the total four-momentum in the c.m. frame, and q being the internal meson four-momentum. The loop function diverges logarithmically and needs to be regularized. We employ the *cutoff method* that implies restricting the momentum integrals up to a value Λ, which should be related to the dynamical scale that has been integrated out in our model, like the mass of the lighter vector mesons being exchanged in the t-channel diagram. Taking these considerations into account, we choose $\Lambda = 800$ MeV.

The resonances are generated as poles of the scattering amplitude T_{ij}, analytically continued to the so-called *second Riemann sheet* of the complex energy plane. The behavior of the amplitude in the vicinity of the pole allows one to obtain the couplings g_i of the resonance to the various meson-baryon channels, as well as the compositeness χ_i, which measures the amount of a given meson-baryon component in the resonance. See, for example, Ref. [23] for more details on the formalism and explicit definitions.

Results and discussion.—Following our model, in the PB sector we obtain a dynamically generated hidden-charm double-strange baryon resonance at 4493 MeV with a width of 74 MeV. As can be seen from the detailed information given in Table II, this resonance couples strongly to the $\bar{D}\Omega_c$ and $\bar{D}_s\Xi_c'$ channels and is dominantly composed by $\bar{D}\Omega_c$ states. Being generated by the S-wave interaction of a 0^- pseudoscalar meson with a $1/2^+$ baryon in the $(I,S) = (1/2, -2)$ sector, the $P_{\Psi_{ss}}^{\Xi}(4493)$ state is predicted to have spin parity $J^\pi = 1/2^-$.

TABLE II. Energy, width, couplings to meson-baryon states, and compositeness of the PB molecular $P_{\Psi_{ss}}^{\Xi}(4493)$ state.

$0^- \oplus 1/2^+$ PB interaction in the $(I,S) = (1/2, -2)$ sector				
$P_{\Psi_{ss}}^{\Xi}(4493)$		$M_R = 4493.35$ MeV	$\Gamma_R = 73.67$ MeV	
	Threshold Energy (MeV)	g_i	$\lvert g_i \rvert$	χ_i
$\eta_c\Xi$	4298	$-1.60 + i0.34$	1.63	0.220
$\bar{D}_s\Xi_c$	4437	$-0.17 + i0.27$	0.32	0.019
$\bar{D}_s\Xi_c'$	4545	$-2.41 + i0.58$	2.48	0.398
$\bar{D}\Omega_c$	4564	$3.59 - i0.77$	3.67	0.711

We observe that the $P_{\Psi_{ss}}^{\Xi}(4493)$ appears below the thresholds of the $\bar{D}\Omega_c$ and $\bar{D}_s\Xi_c'$ channels, which participate strongly in its generation, and can decay only into the two lightest ones. It is clear, however, that the most probable decay process will be $P_{\Psi_{ss}}^{\Xi}(4493) \to \eta_c\Xi$, as the coupling to this lowest-energy channel is almost an order of magnitude larger than that to $\bar{D}_s\Xi_c$, together with the fact that the available phase space is also much larger. Therefore, this state could be seen from the invariant mass spectrum of $\eta_c\Xi$ pairs in the decays $\Xi_b \to \Xi\eta_c\phi$ and $\Omega_b \to \Xi\eta_c\bar{K}$.

It is interesting to compare our results with those of other works using similar models. First of all, we note that a dynamically generated state, strongly coupled to the $\bar{D}\Omega_c$ and $\bar{D}_s\Xi_c'$ channels, is also found in Ref. [7] but at a much smaller energy, $M_R \simeq 3800$ MeV. Such a substantial difference has to do with the rather different method and parameters of the regularization scheme employed. While we use the cutoff method with $\Lambda = 800$ MeV, the authors of Ref. [7] regularize the loop function imposing the requirement $G_l(\mu) = 0$, at μ given by $\mu = \sqrt{m_{\rm th}^2 + M_{\rm th}^2}$, with $m_{\rm th}$ and $M_{\rm th}$ the masses of the meson and baryon, respectively, of the lightest possible channel, namely, $\pi\Xi$ in the case of Ref. [7]. Enforcing this regularization requirement amounts to using in our model of a cutoff value of $\Lambda \simeq 2800$ MeV, which is unreasonably large in our opinion.

We next compare our results with those of Ref. [9], where the loop function is calculated in a way similar to ours, but the resonance strongly coupled to the $\bar{D}\Omega_c$ and $\bar{D}_s\Xi_c'$ states is not discussed, possibly because the mild attraction induced by J/Ψ exchange is neglected by taking $C_{44} = 0$ (which in our case is equivalent to setting $\kappa_{cc} = 0$) and the remaining diagonal channels have null or repulsive interactions. Ignoring the small value of κ_{cc} is usually a sufficiently good approximation. In fact, the mild attractive character of $C_{44} = \kappa_{cc} = 1/9$ would not be sufficient to produce a $\bar{D}\Omega_c$ bound state in an uncoupled-channel

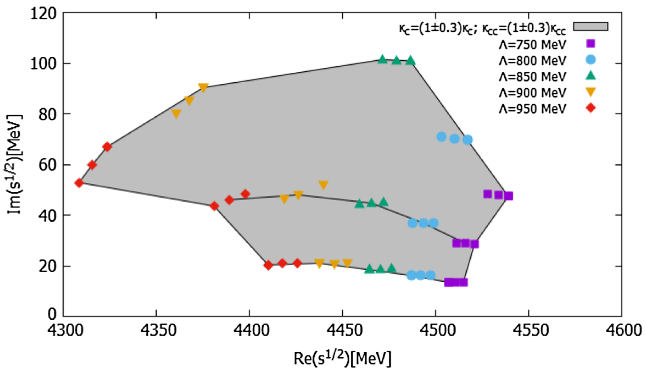

FIG. 2. Region in the complex energy plane where the molecular $P^{\Xi}_{\Psi ss}$ pentaquark can be found. The colored symbols indicate the pole position of the resonance for different cutoff values in the range (750–950) MeV and nine different SU(4)-breaking parameters, corresponding to the possible combinations of the values $(0.7, 1.0, 1.3)\kappa_c$ and $(0.7, 1.0, 1.3)\kappa_{cc}$. The upper dots are obtained with $1.3\kappa_c$ and the lower ones with $0.7\kappa_c$. The dependence on the variation of κ_{cc} is mild and is reflected in the separation within each three-symbol group. The black lines are merely to guide the eye and join the results obtained with different cutoff values for the combinations with $1.3\kappa_c, 0.7\kappa_{cc}$ (upper line), κ_c, κ_{cc} (middle line), and $0.7\kappa_c, 1.3\kappa_{cc}$ (lower line).

calculation, as we have numerically checked. However, in this particular sector, one finds a sizable nondiagonal coefficient, $C_{43} = -\sqrt{2}$, which, via coupled channels, adds enough attraction to make the dynamical generation of the new molecular state possible. We have tested that the minimum strength of C_{43} which can still generate this resonance is $-0.75\sqrt{2}$. We are, thus, observing a very interesting phenomenon, uniquely related to the coupled-channel dynamics, which enhances the mild attraction of the $\bar{D}\Omega_c$ interaction to produce a bound state. This is analogous to what happens to the deuteron, which appears as a bound state of the coupled-channel ${}^3S_1 - {}^3D_1$ nucleon-nucleon interaction but would disappear in an uncoupled calculation [24].

While our model relies on SU(4) symmetry, it is already violated to some extent by the use of the physical masses for the mesons and baryons in the interaction kernel and in the loop function. However, we would like to analyze how the generated resonance is affected when we introduce up to an additional 30% of SU(4) symmetry violation in the coupling vertices of the transitions mediated by the exchange of heavy mesons. This is implemented in practice by multiplying κ_c and κ_{cc} by a factor varying in the range (0.7–1.3). We also investigate the sensitivity of the pole position to the cutoff parameter Λ, which we vary from 750 until 950 MeV. The results of all these calculations form the gray area displayed in Fig. 2. It is seen that modifications of the cutoff produce sizable variations in the mass of the resonance but a moderate effect on its width. In contrast, a modification of κ_c produces important variations in the

TABLE III. Energy, width, couplings to meson-baryon states, and compositeness of the VB molecular $\Xi(4633)$ state.

$1^- \oplus 1/2^+$ VB interaction in the $(I, S) = (1/2, -2)$ sector				
$P^{\Xi}_{\Psi ss}(4633)$		$M_R = 4633.38$ MeV	$\Gamma_R = 79.58$ MeV	
	Threshold Energy (MeV)	g	$\lvert g_i \rvert$	χ_i
$J/\psi\Xi$	4415	$-1.62 + i0.38$	1.66	0.252
$\bar{D}^*_s\Xi_c$	4581	$-0.143 + i0.32$	0.34	0.022
$\bar{D}^*_s\Xi'_c$	4689	$-2.49 + i0.67$	2.58	0.406
$\bar{D}^*\Omega_c$	4706	$3.67 + i0.89$	3.78	0.740

width of the resonance, while the mass is less affected, except for the larger cutoff and κ_c values. This is easily understood from inspecting the coefficients in Table I, which show that the size of the parameter κ_c is directly affecting the couplings of the heavier channels to the lighter one $\eta_c\Xi$, to which the resonance decays. The overall conclusion is that, although the mass and the width depend on the model parameters, the appearance of a pole is a robust outcome in all these calculations, giving support to our claim of the probable existence of an $(I, S) = (1/2, -2)$ molecular-type pentaquark $P^{\Xi}_{\Psi ss}$ with spin parity $J^P = 1/2^-$.

Proceeding in a similar way, we obtain in the VB sector a resonance at 4633 MeV with a width of around 80 MeV, in agreement with Ref. [14], strongly coupled to the $\bar{D}^*\Omega_c$ and $\bar{D}^*_s\Xi'_c$ channels, dominantly composed by $\bar{D}^*\Omega_c$ states, and decaying mostly to $J/\Psi\Xi$ pairs. The detailed values of the pole position, couplings, and compositeness can be found in Table III. Note that this $P^{\Xi}_{\Psi ss}(4633)$ state is degenerate in spin, since, having been obtained from the interaction in the S wave of $J^P = 1^-$ vector mesons with $J^P = 1/2^+$ baryons, it can have either $J^P = 1/2^-$ or $J^P = 3/2^-$. Similarly to the PB resonance discussed before, the $P^{\Xi}_{\Psi ss}(4633)$ pentaquark could be seen as a peak in the invariant mass spectrum of $J/\Psi\Xi$ pairs produced in the decays $\Xi_b \to \Xi J/\Psi\phi$ and $\Omega_b \to \Xi J/\Psi\bar{K}$.

Conclusions.—Stimulated by the recent discoveries by the LHCb Collaboration of hidden-charm pentaquark states with strangeness $S = 0$ and $S = -1$, some of which could be associated to the predicted meson-baryon molecular states found in unitary models based on vector-meson exchange interactions, we have revisited these models to study the possible existence of pentaquarks with strangeness $S = -2$.

Employing realistic regularization parameters, we predict double-strangeness pentaquarks of molecular nature around 4500 and 4600 MeV. This unexpected result of the model was overlooked before, due to the dominantly repulsive interaction between the meson and the baryon in various channels of the basis employed. However, we have found that bound states are indeed generated in a very specific and unique way, via a strong nondiagonal attraction between the two heaviest meson-baryon channels.

Our Letter should stimulate experiments looking for these type of pentaquarks, the discovery of which would enrich the family of their already-observed $S = 0$ and $S = -1$ pentaquark partners. The absence in this sector of a long-range interaction mediated by pion exchange also makes the search for these states especially interesting. If they do exist, their interpretation as molecules would require a change of paradigm, since they could be bound only through heavier-meson exchange models as the one employed in this Letter.

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