REACTIONS LOOKING FOR HIDDEN CHARM PENTAQUARKS WITH OR WITHOUT STRANGENESS*

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Results for five reactions, $\Lambda_b \to J/\psi K^- p$, $\Lambda_b \to J/\psi \eta \Lambda$, $\Lambda_b \to J/\psi \pi^- p$, $\Lambda_b \to J/\psi K^0 \Lambda$ and $\Xi_b^- \to J/\psi K^- \Lambda$ are presented on predictions made for molecular states of hidden charm, with or without strangeness, evaluating invariant mass distributions for $J/\psi p$ or $J/\psi \Lambda$. We show that in all of these reactions, one finds peaks where the pentaquark states show up.

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1. Introduction

The recent observation of signals on the $J/\psi p$ mass distribution in the $\Lambda_b \to J/\psi p K^-$ decay [1, 2], interpreting them in terms of two pentaquark states, $P_c(4380)$, $P_c(4450)$, with widths around 200 MeV and 40 MeV respectively, has stirred a lot of excitement in the hadron community.

Among the ideas proposed to explain the states, meson–baryon molecules have been suggested. Summaries of the theoretical and experimental work done can be seen in Refs. [3, 4], and a thorough review on the subject has been presented in [5].

Here, we concentrate on the hypothesis that the states observed are of molecular type. The molecular nature is quite appealing, since predictions for states of hidden charm, that could be naturally associated to these observed states, had been done before. Indeed, in [6, 7] baryon states of hidden charm were found in the study of the interaction of the $\bar{D}\Sigma_c$–$\bar{D}\Lambda_c$, $\bar{D}^*\Sigma_c$–$\bar{D}^*\Lambda_c$ coupled channels as main building blocks, together with decay channels in the light sector and the $\eta_c N$ and $J/\psi N$ states. Related studies followed and in [8], an admixture of spin flavor symmetry in the light sector and Heavy Quark Spin symmetry, HQSS, was used and states of hidden charm similar to those predicted in [6, 7] were found. Similar results to those of [6, 7] were found in [9] using HQSS and the local hidden gauge approach to evaluate the matrix elements of HQSS. More work on this is done in [10], where a mixture of Vector-Baryon (VB) and Pseudoscalar-Baryon (PB) states is allowed in coupled channels such that one can have a better hold on the decay width of the states.

In [6, 7], it was, moreover, found that in the strange sector, there were also some resonances with hidden charm and strangeness $S = -1$, related to those found in the hidden charm $S = 0$ sector. With this perspective, we shall discuss in the present work several promising reactions, some of which are already under analysis by the LHCb Collaboration.

2. The $\Lambda_b^0 \to J/\psi p K^-$ reaction and the $P_c(4380)$ and $P_c(4450)$ states

In this section, we show a test of consistency of the results of the experiment [1] and previous theoretical results obtained for hidden charm states [6, 7, 9] and for the $K^- p$ mass distribution in the $\Lambda_b^0 \to J/\psi p K^-$ reaction in [11], following similar steps as done in the B^0 and B_s^0 decays into $J/\psi \pi^+\pi^-$ in [12] (see also recent review in [13]). The details are seen in [15].

The relevant mechanisms for the $\Lambda(1405)$ production in the $\Lambda_b^0 \to J/\psi p K^-$ decay in Ref. [11] are depicted in Figs. 1 (a) and (b). In Fig. 1 (a), the u and d quarks of the initial Λ_b remain as spectators in the process and carry isospin $I = 0$, as in the initial state, producing, together with the s quark, an isoscalar baryon after the weak process, and hence a meson–baryon system in $I = 0$ after the hadronization of the sud state. It is interesting to see that in the analysis of data in [1] only Λ^* states were seen, as predicted in [11]. The hadronization produces a meson and a baryon, in particular $K^- p$. The final meson–baryon state then undergoes final state interaction in coupled channels, Fig. 1 (b), from where the $\Lambda(1405)$ is dynamically produced.

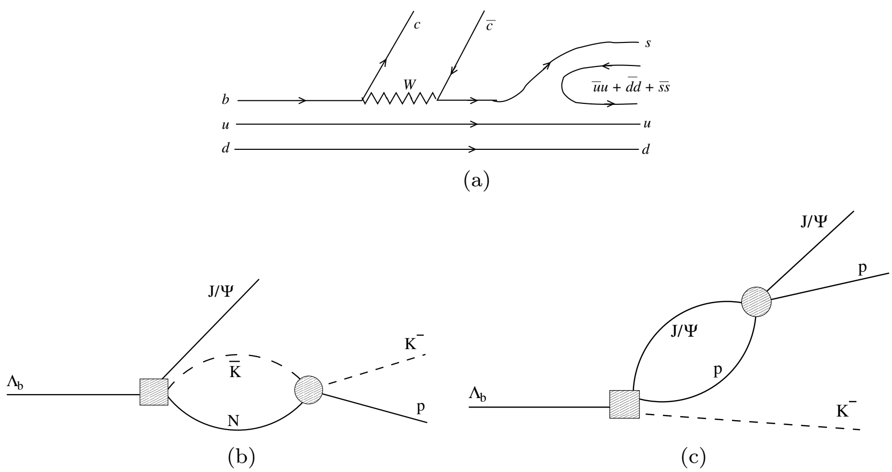

Fig. 1. Mechanisms for the $\Lambda_b \to J/\psi K^- p$ reaction implementing the final state interaction

In the chiral unitary scheme of [14], the $\Lambda(1405)$ appears dynamically in the highly non-linear dynamics involved in the unitarization procedure showing up in the t_{ij} amplitudes. These amplitudes contain two poles for the $\Lambda(1405)$ resonance at $1352 - 48i$ MeV and $1419 - 29i$ MeV [14]. The highest mass $\Lambda(1405)$, couples mostly to $\bar{K}N$, and is the one relevant in the present work.

On the other hand, in Refs. [6, 9], it was shown that the $J/\psi\, N$ final state interaction in coupled channels, considering the $\bar{D}^* \Lambda_c$, $\bar{D}^* \Sigma_c$, $\bar{D}\Sigma_c^*$ and $\bar{D}^* \Sigma_c^*$ channels, produces poles in the $J^P = 3/2^-$, $I = 1/2$ sector at $4334 - 19i$ MeV, $4417 - 4i$ MeV and $4481 - 17i$ MeV, which couple sizeably to $J/\psi\, p$ (see Table II in Ref. [9]). Thus, the $J/\psi\, p$ invariant mass distribution in the $\Lambda_b \to J/\psi\, K^- p$ decay should show the shape of these resonances. The mechanism for the final $J/\psi\, N$ state interaction is depicted in Fig. 1 (c). The filled circle in that figure represents the final $J/\psi\, p \to J/\psi\, p$ unitarized scattering amplitude, which according to [9], can be well-represented by a Breit–Wigner (BW) form

$$t_{J/\psi\, p \to J/\psi\, p} = \frac{g^2_{J/\psi\, p}}{M_{J/\psi\, p} - M_R + i\frac{\Gamma_R}{2}}\,, \tag{1}$$

where $M_{J/\psi\, p}$ is the $J/\psi\, p$ invariant mass and M_R (Γ_R) the mass (width) of the $P_c(4450)^+$. In Eq. (1), $g_{J/\psi\, p}$ stands for the coupling of the dynamically generated resonance to $J/\psi\, p$, for which values from about 0.5 to 1 are obtained in Refs. [6, 9].

In Fig. 2, we show the results for the $K^- p$ and $J/\psi\, p$ invariant mass distributions obtained in [15] compared to the experimental data of Ref. [1]. Because of an unknown factor, we have an arbitrary normalization, but the same for both panels. In the data shown for the $K^- p$ mass distribution, only the $\Lambda(1405)$ contribution of [1] is included. Similarly, the experimental $J/\psi\, p$ mass distribution shown in Fig. 2 (b) considers only the contribution from the $P_c(4450)^+$. The different curves are evaluated considering different values for the coupling of the $P_c(4450)^+$ to $J/\psi\, p$, ($g_{J/\psi\, p} = 0.5$, 0.55 and 0.6), normalizing the unknown factor for each value of $g_{J/\psi\, p}$ such that the peak of the $J/\psi\, p$ distribution agrees with experiment. Therefore, the accumulation of strength close to the threshold is due to the tail of the $\Lambda(1405)$ resonance, which lies below the $K^- p$ threshold. The relevant message from the former exercise is that a fair agreement with experiment for the relative size of the $K^- p$ and $J/\psi p$ distributions can be reached with the previous theoretical findings, in which the $P_c(4450)$ peak would correspond to a molecular state of $\bar{D}^* \Sigma_c - \bar{D}^* \Sigma_c^*$ nature [6, 9] and the $K^- p$ distribution at low invariant masses, reflecting the $\Lambda(1405)$, is produced according to the mechanism developed in [11].

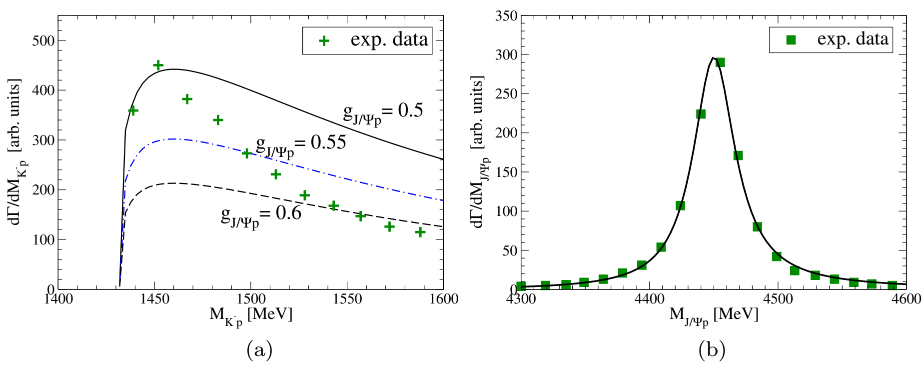

Fig. 2. Results for the $K^- p$ and $J/\psi\, p$ invariant mass distributions compared to the data of Ref. [1].

3. A hidden-charm $S = -1$ pentaquark from the decay of Λ_b into $J/\psi\eta\Lambda$ states

The same mechanism as shown in Fig. 1 (a) can lead to other combinations of meson–baryon in the final state. Indeed, the $\eta\Lambda$ is one of the channels which is already produced at the tree level in the first step after the hadronization. If we look at the $J/\psi\eta\Lambda$ final state, this channel will be produced with a strength similar to the one of $J/\psi K^- p$, which is already observed. Certainly there will be the final state interaction of the meson–baryons produced at the first step to give finally the $\eta\Lambda$. And certainly, we can also have rescattering of J/ψ with the Λ. The question now is whether there is some partner pentaquark of those observed in the $J/\psi p$ mass distribution in the $\Lambda_b \to J/\psi K^- p$ reaction, which could show up in the $J/\psi\Lambda$ distribution. This partner state was found in [6] and it couples to $\bar{D}^*\Xi_c$, $\bar{D}^*\Xi_c'$ and $J/\psi\Lambda$.

In [16], predictions are made stating that as far as the coupling of the resonance to $J/\psi\Lambda$ is of the order of 0.5, which is found in [6], one should see clear signals in this reaction.

4. The hidden-charm pentaquark state in $\Lambda_b^0 \to J/\psi p\pi^-$ decay

In the present section, we shall discuss the $\Lambda_b^0 \to J/\psi p\pi^-$ reaction which was measured in [17]. The results have a smaller statistics than those of Ref. [1], but in retrospective they are very valuable. In [18], the reaction was studied and $p\pi^-$ as well as $J/\psi p$ invariant mass distributions were calculated. It was found that the peak observed was consistent with the description given before for the $\Lambda_b^0 \to J/\psi p K^-$ decay.

5. The $\Lambda_b \to J/\psi K^0\Lambda$ reaction and the hidden-charm pentaquark state with strangeness

In this section, we report on the study of the $\Lambda_b \to J/\psi K^0\Lambda$ reaction in [19]. The mechanism is now the same as in the former sections, but instead of looking for $\pi^- p$ in the final state, we look now at its coupled channel $K^0\Lambda$.

A clear signal was also seen in the $J/\psi\Lambda$ mass distribution. The signal can depend on the precise values of the couplings and the width of the states, but the message of [19] is that the peaks are visible over a wide variation of the parameters around the values chosen according to Refs. [6, 7].

6. The hidden-charm pentaquark state with strangeness $S = -1$ from Ξ_b^- decay into $J/\psi K^- \Lambda$

Finally, we report on the work of [20] for the $\Xi_b^- \to J/\psi K^- \Lambda$ reaction, where the hidden-charm strange state discussed in the former section shows up again.

We observe a clear structure around 4650 MeV on top of the background when the $J/\psi\Lambda$ interaction is taken into account. By changing M_R, the peak position changes accordingly, but a clear signal is observed in all cases as long as the width is smaller than 100 MeV [20]. We stress, however, that the strength of the signal will depend strongly on the coupling of the hidden charm state to the $J/\psi\Lambda$, *i.e.*, $g_{J/\psi\Lambda}$, but, again, it was shown in [20] that the signal would be still visible with large changes of this coupling.

7. Further remarks

Final refinements in the works reported here show that the coherent sum of the amplitudes for pseudoscalar-baryon and J/ψ-baryon holds strictly for $J^P = 1/2^-$ of the J/ψ-baryon. For $J^P = 3/2^-$, other production amplitudes must be considered, but the conclusions obtained about the observability of the predicted states are the same. Considerations are also made about indirect ways of producing the J/ψ-baryon resonance in [16], as the direct production of $\bar{D}^{*0}\Xi_c'\eta$ followed by $\bar{D}^{*0}\Xi_c' \to J/\psi\Lambda$. Once again, the conclusion is that the observation of the predicted strange hidden-charm state should be rather clean.

8. Conclusions

From the perspective that the observed hidden-charm pentaquark states without strangeness in Ref. [1] might be molecular states of $\bar{D}^*\Sigma_c$–$\bar{D}^*\Sigma_c^*$ nature, as was predicted before the experiment was performed, and the fact that hidden-charm states with strangeness were simultaneously predicted, we have looked into some reactions where these states could be seen. We reported on predictions for five different reactions, and neat peaks in the $J/\psi p$ or $J/\psi\Lambda$ mass distributions show up in the calculations. It would be most interesting to perform such experiments, and some of them are already under analysis by the LHCb Collaboration.

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REFERENCES

[1] R. Aaij *et al.* [LHCb Collaboration], *Phys. Rev. Lett.* **115**, 072001 (2015).
[2] R. Aaij *et al.* [LHCb Collaboration], *Chin. Phys. C* **40**, 011001 (2016).
[3] T.J. Burns, *Eur. Phys. J. A* **51**, 152 (2015).
[4] R. Chen, X. Liu, S.L. Zhu, *Nucl. Phys. A* **954**, 406 (2016) [arXiv:1601.03233 [hep-ph]].
[5] H.X. Chen, W. Chen, X. Liu, S.L. Zhu, *Phys. Rep.* **639**, 1 (2016) [arXiv:1601.02092 [hep-ph]].
[6] J.J. Wu, R. Molina, E. Oset, B.S. Zou, *Phys. Rev. C* **84**, 015202 (2011).
[7] J.J. Wu, R. Molina, E. Oset, B.S. Zou, *Phys. Rev. Lett.* **105**, 232001 (2010).
[8] C. Garcia-Recio *et al.*, *Phys. Rev. D* **87**, 074034 (2013).
[9] C.W. Xiao, J. Nieves, E. Oset, *Phys. Rev. D* **88**, 056012 (2013).
[10] T. Uchino, W.H. Liang, E. Oset, *Eur. Phys. J. A* **52**, 43 (2016).
[11] L. Roca, M. Mai, E. Oset, U.-G. Meißner, *Eur. Phys. J. C* **75**, 218 (2015).
[12] W.H. Liang, E. Oset, *Phys. Lett. B* **737**, 70 (2014).
[13] E. Oset *et al.*, *Int. J. Mod. Phys. E* **25**, 1630001 (2016).
[14] L. Roca, E. Oset, *Phys. Rev. C* **88**, 055206 (2013).
[15] L. Roca, J. Nieves, E. Oset, *Phys. Rev. D* **92**, 094003 (2015).
[16] A. Feijoo, V.K. Magas, A. Ramos, E. Oset, arXiv:1512.08152 [hep-ph].
[17] R. Aaij *et al.* [LHCb Collaboration], *J. High Energy Phys.* **1407**, 103 (2014).
[18] E. Wang *et al.*, *Phys. Rev. D* **93**, 094001 (2016).
[19] J.X. Lu *et al.*, *Phys. Rev. D* **93**, 094009 (2016).
[20] H.X. Chen *et al.*, *Phys. Rev. C* **93**, 065203 (2016) [arXiv:1510.01803 [hep-ph]].