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Predictions for pentaquark states of hidden charm molecular nature and comparison with experiment

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Abstract. Predictions for hidden charm molecules, with and without strangeness, were made prior to the LHCb experiment. We discuss these issues and how these states can be observed in the 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 $\Xi_b^- \to J/\psi K^- \Lambda$ by looking at the invariant mass distributions for $J/\psi p$ or $J/\psi \Lambda$.

1 Introduction

Peaks observed recently in the $J/\psi p$ mass distribution in the $\Lambda_b \to J/\psi p K^-$ decay [1, 2], were interpreted in terms of two pentaquark states, $P_c(4380)$, $P_c(4450)$, with widths around 200 MeV and 40 MeV respectively. Summaries of the theoretical and experimental work concerning these findings 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

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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 control on the decay width of the states.

In [6, 7] it was also 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

The pentaquarks were found in the $\Lambda_b^0 \to J/\psi p K^-$ reaction, by looking at the $J/\psi p$ mass distribution. At the same time, the pK^- mass distribution was also discussed. It is interesting to mention that this reaction had been studied before theoretically [11] and predictions were made for the pK^- and $\pi\Sigma$ mass distributions, 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]). It is interesting to recall that the predicctions made for the pK^- mass distribution were in agreement with the $\Lambda(1405)$ contribution deduced from the partial wave analyis of [1, 2]. The consistency of the results of [6] with those of the LHCb experiment was shown in [14].

A recent reanalysis of the $J/\psi p$ and $K^- p$ mass distributions has been done recently, by constructing the suited amplitudes to the possible quantum numbers of the $J/\psi p$ system and taking into account explicitly the $K^- p$ interaction within the chiral unitary approach [15]. What is found there is that the mass distributions by themselves do not favour any particular spin parity for the $J/\psi p$ and there is no compelling need for the broad pentaquark state. Thus, it must be other experimental information what favours one or another assignment.

In the chiral unitary scheme of [16] 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 [16]. 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, as indeed has been shown in [1].

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

The same mechanism that drives the $\Lambda_b^0 \to J/\psi p K^-$ reaction 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 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 [17] 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 [18]. The results have a smaller statistics than those of Ref. [1], but in retrospective they are very valuable. In [19] 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 [20]. 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 [20] 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 [21] for the $\Xi_b^- \to J/\psi K^- \Lambda$ reaction, where again 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 [21]. 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 [21] that the signal would still be visible with large changes of this coupling.

7 Further remarks

Considerations are also made about indirect ways of producing the J/ψ- baryon resonance in [17], 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. A recent review of all these reactions is available in [22].

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