Unanswered Questions in Charmed Baryon Physics

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This is an experimentalist’s list of questions concerning the physics of the charmed baryon sector which have no satisfactory answer.

I. INTRODUCTION

In many conferences experimentalists talk about carefully justified results rather than analyses they are actively pursuing, and theorists often present work on models which pertain to measurements that cannot be performed in the near future. Sometimes this leads to a disappointing lack of real communication between the two groups. I give this talk as an experimentalist, pointing out features of the data that I do not believe have had satisfactory explanations, but which might in fact be easily comprehensible. All the data presented is freely available on the web and I am not representing any experiment.

II. THE $\Lambda_c(2880)^+$

In $\Lambda^+$ spectroscopy many states have been found, and can all be explained from a model where the $\Lambda^+$ comprises a heavy (charm) quark and a light di-quark. This configuration predicts a plethora of states. For instance, the addition of one unit of orbital angular momentum can be placed between the heavy quark and light di-quark (a “$\lambda$” excitation) or between the light quarks in the di-quark (a “$\rho$” excitation). Once two units of orbital angular momentum are allowed, there are 3 different possibilities of their placement. Each of these combinations, with its particular “light-quark degrees of freedoms”, can then combine with the heavy-quark spin to make doublets.

Figure 1 shows the $M(\Lambda^+_c\pi^+\pi^-)$ mass in $e^+e^-$ annihilation data from Belle. The $\Lambda_c(2880)$ sticks out from the background even though there must be many states around that mass - this feature caused a surprise when first found. The state is generally considered to be a “Roper”-like radial excitation. Next is the prominent $\Lambda_c(2625)$ which extends beyond the top of the plot, and then the $\Lambda_c(2593)$ peak which is distorted by its proximity to the $\Sigma_c(2455)\pi$ threshold.

The identification of the quark structure of the $\Lambda_c(2593)$ was made on discovery as being the $J^P = \frac{3}{2}^-$ lowest-mass (“$\lambda$”) orbital excitation. Based on this identification, together with that of the $\Lambda_c(2625)$ as its $J^P = \frac{3}{2}^-$ partner, the scale was set for the excitation energy ($\approx 300$ MeV/$c^2$) for a $\lambda = 1$ orbital excitation and the splitting between the states of $\approx 30$ MeV/$c^2$. According to the standard potential model, the first should be roughly independent of heavy-quark mass, and the latter approximately inversely proportional to the heavy-quark mass. Thus, the decay to $\Sigma_c(2520)\pi$ so that the state is narrow. Why is this?

III. THE $\Lambda_c(2593)$

As we go down to lower masses in the same spectrum (Fig. 1), there is a very large $\Lambda_c(2765)$ resonance which is only given one “star” in the Particle Data Book but clearly exists, and is generally considered to be a “Roper”-like radial excitation. Next is the prominent $\Lambda_c(2625)$ which extends beyond the top of the plot, and then the $\Lambda_c(2593)$ peak which is distorted by its proximity to the $\Sigma_c(2455)\pi$ threshold.

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this model thus predicted the masses (as well as the properties) of more than six other states; the \( \Xi_c(2790) \) and \( \Xi_c(2815) \) iso-doublets, and the \( \Lambda_b(5912) \) and \( \Lambda_b(5920) \) have all been subsequently observed. Figure 2 shows how the expected pattern of masses has been confirmed.

Despite the success of these predictions, recent papers have conjectured that the \( \Lambda_c(2593) \) can be explained as a molecular state \([8]\) or a dynamically generated meson-baryon state \([9]\). The former is motivated by the fact that its mass is very close to the sum of the \( \Sigma_c(2455) \) and \( \pi \) masses. However, it can be seen in Fig. 2 that of the eight states, four have masses above the kinematic threshold of their preferred decays, three have masses below (which keeps the states very narrow) - it is hardly surprising that one has a mass that coincides, within the fuzziness caused by the isospin mass-splitting of the transition pions, with its particular threshold. My questions are, if the \( \Lambda_c(2593) \) is not the \( \lambda = 1 \) orbital excitation, how do you explain that the model correctly predicted the other six states? Secondly, what parameter of the \( \Lambda_c(2593) \) should we be measuring in order to discriminate between the models? The resonance shape is clearly complicated by the threshold, but as yet there is nothing observed inconsistent with the quark content being dominated by the simplest model. We rate scientific theories by the validity of their predictions, and the (heavy quark)/(light di-quark) model for heavy baryons has served us very well in this respect. Of course, in any conversation on the inner structure of baryons, we must always be aware that there is nothing observed inconsistent with the quark content being dominated by the simplest model. We rate scientific theories by the validity of their predictions, and the (heavy quark)/(light di-quark) model for heavy baryons has served us very well in this respect. Of course, in any conversation on the inner structure of baryons, we must always be aware that no one simple model will give the complete story.

IV. \( \Xi_c \) ISOSPIN SPLITTING

There has been considerable progress in recent years on the \( \Xi_c \) spectrum. There are six iso-doublets with well-measured masses, plus several other states not as well defined. When tabulating the masses of the six (Tab. 1), it appears that the isospin splitting divides into two groups, one with around 3.5 MeV/\( c^2 \), and one with less than 1 MeV/\( c^2 \). The first group all have a spin-0 di-quark, and the latter group have a spin-1 di-quark. My question, is this a rule that can then be applied to help identify higher mass states that are being discovered?

| Particle \( \Xi_c \)     | \( M(\Xi_c^+) - M(\Xi_c^+) \) MeV/\( c^2 \) |
|-------------------------|---------------------------------------------|
| \( \Xi_c(2790) \)      | \(-3.3 \pm 0.4 \)                           |
| \( \Xi_c(2645) \)      | \(-0.9 \pm 0.5 \)                           |
| \( \Xi_c(2815) \)      | \(-3.5 \pm 0.5 \)                           |
| \( \Xi_c(2980) \)      | \(-4.8 \pm 0.5 \)                           |
| \( \Xi_c^0 \)          | \(-0.8 \pm 0.5 \)                           |
| \( \Xi_c(2790) \)      | \(-3.3 \pm 0.6 \)                           |

V. \( \Omega_c^0 \) DECAYS

Of the four weakly decaying charmed baryons, the least is known about the \( \Omega_c \) (css). The general knowledge of its decays seemed uncontroversial until recently. The lifetime of the \( \Omega_c^0 \) had been measured by three experiments to be very short, and this agreed with early ideas on the expected lifetime hierarchy of the four lifetimes \([11]\). However, of the three experiments measuring the lifetimes \([12][14]\), one had signals in various modes but never managed to publish an \( \Omega_c^0 \) mass \([12]\), and another used a decay mode that has never been seen by other experiments \([13]\). Despite a search \([15]\), I note that if you over-estimate your signal yields you tend to produce a short lifetime measurement. Recently LHCb found a much longer lifetime \([16]\), showing that the knowledge of the \( \Omega_c^0 \) weak decays was less definitive than had been thought. (I note that one paper \([17]\) brought attention to this problem before the experimental measurement). Information on the \( \Omega_c^0 \) branching fractions is comparatively scarce, but one aspect that stands out is that the branching ratio \( B(\Omega_c^0 \rightarrow \Omega^- \pi^+ \pi^- \pi^+) / B(\Omega_c^0 \rightarrow \Omega^- \pi^+) \) is much less than the analogous ratios for the other charmed baryons (Tab. 1). In the most simple decay models, these should all be similar - it easy to see how factors of two or three can arise from differences in phase-space etc. but the difference of a factor of ten seems very large. There is a similar trend (though not as marked) with the decay into \( \Omega^- \pi^+ \pi^0 \). My question is whether these branching fractions tell us anything basic about the differences in the decays of the weakly decaying charmed baryons.
VI. EXCITED $\Omega_c^0$ SPECTROSCOPY

This is one subject where, rather than too few, there are too many answers. The LHCb [18] discovery of five narrow states brought an immediate flood of explanations. The most obvious (though naive) explanation is that the first $\lambda = 1$ excitation states for the $\Omega_c^0$ will in fact be a quintuplet of states, and given that higher spin usually indicates higher mass, the states can be labeled as $J^P = (\frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-, \frac{7}{2}^-, \frac{9}{2}^-)$ (The Belle analysis [19] showed four of the states, but the last one is missing. This did not strike people as surprising given that the fifth (i.e. highest mass) of the LHCb quintuplet was their smallest peak. However, in $e^+e^-$ continuum production, the production rates of states within a family occurs via the $\sqrt{2}J+1$ rule. This has been verified in a variety of systems [20]. Even considering mass suppression, and the possibility of decays to $\Xi'_c$, it would seem surprising that the highest spin state would not be seen by Belle. The plot thickens with the (low statistics) search for these states by LHCb [21] in $\Lambda_b$ decays, which again shows the fifth state missing. My question is this, when considering the possible assignment of states, why do people not take into account the production ratios? For $e^+e^-$ the ratio between the different members of a group (for instance, the $\lambda = 1$ quintuplet) is clear, but no theorist has mentioned them in their attempts to explain the data. In LHCb’s first paper, the situation is more confusing as different production mechanisms are mixed together, and in their second they had no theoretical prediction of the production of the various states in $\Lambda_b$ decays. Surely these ratios could have been predicted in advance of the experiment.

VII. EXCITED $\Sigma_c$ SPECTROSCOPY

It was way back in 2004 that Belle reported the discovery [22] of a new $\Sigma_c$ resonance decaying into $\Lambda_c^+\pi$. The natural explanation is that it is an orbital excitation of the $\Sigma_c$. However, like the $\Omega_c^0$, the $\Sigma_c$ should have a family of a quintuplet of $\lambda = 1$ low-mass states, so why is there only one peak? It is true that some of the five might be too wide to be seen, but I do not believe that any model predicts one to be narrow and four to be wide. This certainly indicates that the peak seen may be due to overlapping states. Very similar results are shown in an (unpublished) analysis using BaBar data [24]. I note that BaBar [25] also see a peak in the same mode, but at a different mass, in $B$ decays. To disentangle these observations what we need is not just predictions of the masses and widths of states in this range, but also estimates of the relative production rates, particularly in $B$ decays. I also cannot help asking the question of why LHCb have not shown information on this mass spectrum.

VIII. SUMMARY

I have highlighted several questions which I believe could be fruitful lines of research for theorists. They are just a few of many I have! The charmed baryon sector is already very rich in information, and the next few years we will see more results, so there are many opportunities to make predictions that can be directly tested.

Acknowledgments

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| Table II: Branching ratios comparison for charmed baryons. Data taken from [6]. |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| $\Omega_c^0 \rightarrow \pi^\pm \pi^0 / \Omega^\pm \pi^\pm$ | $\Lambda_c^+ \rightarrow \pi^\pm \pi^0 / \Lambda^\pm \pi^\pm$ | $\Xi^0_c \rightarrow \Xi^\pm \pi^\pm / \Xi^\mp \pi^\pm$ | $\Xi^+_c \rightarrow \Xi^0 \pi^\pm / \Xi^0 \pi^\mp$ |
| $1.97 \pm 0.17$ | $5.46 \pm 0.42$ | Not measured | $4.2 \pm 1.5$ |
| $0.29 \pm 0.04$ | $2.84 \pm 0.34$ | $3.3 \pm 0.5$ | $3.1 \pm 1.0$ |
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