Analysis of the baryonic state $|qc⟩c$

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Abstract

In this note we analyse the structure of the baryonic state $|qc⟩c$ with a spin-0
diquark $[qc]$, as compared to baryonic states $|(qc)c⟩$ and $|q(cc)⟩$ containing internal
spin-1 diquark states. While one can identify the state $|q(cc)⟩$ with the state ob-
served at LHCb, the state $|(qc)c⟩$ could probably be part of the state $Ξ^{±}_cc(3780)$.
Accordingly, the ground state of $|qc⟩c$ can be identified with the state $Ξ^{±}_cc(3520)$.

1 Introduction

Since the publication of first evidences for the existence of doubly charmed baryons by the
SELEX collaboration, this result became probably the most intriguing and controversial
one in modern baryonic physics [1, 2]. The reason for this is that perturbative QCD can
explain neither the SELEX production rate nor the $x_F$ distribution.

However, during the past two years significant progress has been made in understanding
the SELEX result. By involving the intrinsic charm mechanism it was possible to explain the production rate and the kinematics dependencies [3, 4].

The most recent LHCb result on the production of the doubly charmed baryons [5]
illuminated the significant gap between the 3520MeV/$c^2$ SELEX event and the mass
3621.40 ± 0.72(stat) ± 0.27(sys) ± 0.14($Λ_c^+$) MeV/$c^2$ measured by LHCb. This apparent
conflict can be solved by introducing the state $|qc⟩c$ containing a spin-0 diquark $[qc]$, as
this state can be naturally produced by the charmed Fock state comoving with the same
rapidity as the valence quarks of the projectile hadron [6]. In this note we briefly review some consequences of the structure of the baryonic state $|\{q_c\}c\rangle$.

## 2 Isospin splitting of the SELEX states

The analysis of the isospin splitting of the SELEX states implies that double charm baryons are very compact, i.e. the light quark must be very close to the two heavy quarks [7]. This contradicts the usual wisdom. Indeed, within the heavy-diquark concept, the production of the doubly charmed baryon can proceed in two steps. In a first step, due to the reactions $q\bar{q} \rightarrow c\bar{c}c\bar{c}$ or $gg \rightarrow c\bar{c}c\bar{c}$ the production of two $c$ quarks with a small relative momentum will take place, followed by the formation of a $cc$-diquark in the color-antitriplet state. In a second step, the transition of the produced diquark into the baryon is performed. The normalization of the fragmentation of the $cc$-diquark into the double-charm baryons is unknown. However, one is still able to provide some quantitative analysis because the fragmentation function is proportional to the wave function at the origin. The color-antitriplet wave function can be estimated on the basis of information about the color-singlet wave function, $|R(0)[cc]\rangle_3 \sim |R(0)[c\bar{c}]\rangle_1$. This leads to an atom-like structure where the $cc$ diquark forms the compact core while the scale of the light quark is given by the nonperturbative confinement scale [8]. In case of the $S$-wave solution we have the scale hierarchy

$$r_{cc} : r_{QCD} \approx 0.39 : 1$$

where $r_{cc} \sim r_{J/\psi} \sim 0.39\,\text{fm} \simeq (0.5\,\text{GeV})^{-1}$ [9] and $r_{QCD} = 1/(\Lambda_{QCD} \approx 200\,\text{MeV}) \approx 1\,\text{fm}$.

In contrast to this, the production of the doubly charmed baryons at the SELEX experiment is supposed to be due to re-coalesce from a higher Fock state of the proton such as [3 6]

$$|[uu]_3[dc]_3c_3[\bar{c}\bar{c}]_3\rangle$$

which leads to the baryon state $|\{q_c\}c\rangle$ in a natural way. Here the scale will be characterized
by the size of the spin-0 $[qc]$ diquark, given by the Compton wavelength $\lambda_{[qc]} \sim 1/m_{[qc]}$ of the diquark. This naturally provides closeness of the light quark to the two heavy quarks. Note that the peculiarities mentioned here are due to the inclusion of two heavy quarks.

It is interesting to estimate the compactness of such state. The mass $m_{[qc]}$ can be estimated as the effective diquark mass, $m_{\Xi_{cc}} - m_c$, where $m_{\Xi_{cc}}$ is the doubly charmed baryon mass and $m_c$ is the mass of the $c$ quark. In case of the SELEX 3520 MeV event, one has $\lambda_{[dc]} \sim 0.5$ fm which is again in the perfect agreement with the compactness of the SELEX state calculated from isospin splitting [7].

As is emphasized e.g. in Ref. [10], the Fierz identity holds only in case of local field operators. In this case the states $|\{qc\}c\rangle$ and $|q(cc)\rangle$ would be the same state. However, one might think about a nonlocal baryon field operator. Based on works of Diakonov and Petrov [11, 12] and examplified in the instanton liquid model [13], a nonlocal extension of the Nambu-Jona-Lasinio (NJL) model is proposed [14, 15] which, besides being renormalizable and providing confinement for the quarks (in contrast to the original (local) NJL model, see e.g. Refs. [16, 17, 18]), results in a compact baryon (see e.g. Sec. 6.1 of Ref. [19]).

3 The $\Xi_{cc}^{++}(3780)$ state

At a few conferences [20, 21] (cf. also the PhD thesis of Mark E. Mattson [22]), the SELEX collaboration presented a decay process $\Xi_{cc}^{++}(3780) \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ for the state $\Xi_{cc}^{++}(3780)$ with statistical significance of 6.3 $\sigma$. By removing the slower part of the $\pi^+$’s, SELEX observed that roughly 50% of the signal events above background decay weakly and 50% decay strongly (to $\pi^+ \Xi_{cc}^+$. However, this is not possible for a single state. As SELEX did not find a plausible explanation for its decay properties, the result was not published.

Assuming $\Xi_{cc}^{++}(3780)$ to be an excited state $|ucc^*\rangle$, we predict the mass of $|ucc^*\rangle$ by utilizing the predictions of supersymmetric light front holographic QCD (SUSY LFHQCD). This approach was developed by imposing the constraints from the superconformal alge-
braic structure on LFHQCD for massless quarks \[23\]. As has been shown in Refs. \[23, 24\], supersymmetry holds to a good approximation, even if conformal symmetry is strongly broken by the heavy quark mass.

Let us remind the reader that supersymmetric light front holographic QCD, if extended to the case of two heavy quarks, predicts that the mass of the spin-1/2 baryon should be the same as the mass of \( h_c(1P)(3525) \) meson \[24\]. This is well compatible with the SELEX measurement of \( 3520.2 \pm 0.7 \text{ MeV}/c^2 \) for the \( \Xi_{cc}^+ \).

The SUSY LFHQCD prediction for the baryon mass spectra is given by the simple formula

\[
M^2 \propto \lambda (n + L + 1)
\]

where \( \sqrt{\lambda} \approx 0.52 \text{ GeV} \) is the fundamental mass parameter, given by the characteristic mass scale of QCD \[25\]. Using this simple formula, we can estimate the masses of states \([qc]_{3/2} \) (\( n = 1, \ L = 0 \)) and \((qc)_{3/2} \) (\( n = 0, \ L = 1 \)), where \((qc)\) indicates the spin-1 diquark. These states should have the same mass around \( 3730 \text{ MeV}/c^2 \), where the uncertainty of SUSY LFHQCD predictions is at least of the order of 100 MeV. Obviously, we have good agreement with the data for \( \Xi_{cc}^{++}(3780) \).

Investigating the decay properties, the \([qc]_{3/2}\) is more preferable for the weak decay. In contrast to that, \((qc)_{3/2}\) includes a \( D^*\)-meson-like state, leading to the strong decay \( (qc) \rightarrow [qc] + \pi \), similar to \( D^* \rightarrow D + \pi \).

As shown in Ref. \[26, 27\], such a structure does not lead to additional states for baryons consisting only of light quarks \( (m_u, d, s < \Lambda_{QCD}) \). Additional states are found neither for baryons containing both the \( c \) and the \( b \) quark, as the structure \([bq]c\) does not affect the scale hierarchy \[8\]

\[
\lambda_b : \lambda_c : r_{bc} : r_{QCD} \approx 1 : 3 : 9 : 27.
\]

This fact leads to the same ground state masses: the prediction \( M(([bq]c)) = 6750 \pm 100 \text{ MeV} \) of SUSY LFHQCD \[28\], deduced from \( M(([bq]c)) \sim M(B_{c1}) \) is consistent with
the prediction \( M(\Xi_{bc}) \approx 6820 \text{ MeV} \) of the potential model \[8\].

4 Summary

In this note we investigated some consequences of the baryonic state \([q c]c\). As shown in Ref. \[6\], this state can solve the apparent SELEX–LHCb doubly charmed baryon conflict. The theoretical estimate for the compactness of the baryon is in good agreement with similar estimates from isospin splitting. In addition, we gave estimates for the mass and the decay properties of \( \Xi_{cc}^{++}(3780) \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+ \).

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References

[1] M. Mattson et al. [SELEX Collaboration], Phys. Rev. Lett. 89 (2002) 112001

[2] A. Ocherashvili et al. [SELEX Collaboration], Phys. Lett. B628 (2005) 18

[3] S. Koshkarev and V. Anikeev, Phys. Lett. B765 (2017) 171

[4] S. Groote and S. Koshkarev, Eur. Phys. J. C77 (2017) 509

[5] R. Aaij et al. [LHCb Collaboration], Phys. Rev. Lett. 119 (2017) 112001

[6] S.J. Brodsky, S. Groote and S. Koshkarev, arXiv:1709.09903 [hep-ph]

[7] S.J. Brodsky, F.K. Guo, C. Hanhart and U.G. Meißner, Phys. Lett. B698 (2011) 251

[8] V.V. Kiselev and A.K. Likhoded, Phys. Usp. 45 (2002) 455 [Usp. Fiz. Nauk 172 (2002) 497]
[9] K. Nochi, T. Kawanai and S. Sasaki, Phys. Rev. **D94** (2016) 114514

[10] H.X. Chen, Q. Mao, W. Chen, X. Liu and S.L. Zhu,
    Phys. Rev. **D96** (2017) 031501

[11] D. Diakonov and V.Y. Petrov, Nucl. Phys. **B245** (1984) 259

[12] D. Diakonov, V.Y. Petrov and P.V. Pobylitsa,
    Nucl. Phys. **B306** (1988) 809

[13] I.V. Anikin, A.E. Dorokhov and L. Tomio,
    Phys. Part. Nucl. **31** (2000) 509 [Fiz. Elem. Chast. Atom. Yadra **31**, 1023 (2000)]

[14] R.S. Plant and M.C. Birse, Nucl. Phys. **A628** (1998) 607

[15] R.D. Bowler and M.C. Birse, Nucl. Phys. **A582** (1995) 655

[16] U. Vogl and W. Weise, Prog. Part. Nucl. Phys. **27** (1991) 195

[17] S.P. Klevansky, Rev. Mod. Phys. **64** (1992) 649

[18] J. Bijnens, Phys. Rept. **265** (1996) 369

[19] A.H. Rezaeian, [hep-ph/0507304](https://arxiv.org/abs/hep-ph/0507304)

[20] M.A. Moinester *et al.* [SELEX Collaboration], Czech. J. Phys. **53** (2003) B201

[21] J. Engelfried [SELEX Collaboration], eConf C **0610161** (2006) 003

[22] M.E. Mattson, FERMILAB-THESIS-2002-03

[23] H.G. Dosch, G.F. de Téramond and S.J. Brodsky, Phys. Rev. **D91** (2015) 085016

[24] H.G. Dosch, G.F. de Téramond and S.J. Brodsky,
    Phys. Rev. **D92** (2015) 074010; Phys. Rev. **D95** (2017) 034016
[25] S.J. Brodsky, G.F. de Téramond, H.G. Dosch and C. Lorcé, Phys. Lett. B759 (2016) 171

[26] F. Wilczek, “Diquarks as inspiration and as objects,” in M. Shifman (ed.) et al.: From Fields to Strings, vol. 1, pp. 77-93, hep-ph/0409168

[27] A. Selem and F. Wilczek, “Hadron systematics and emergent diquarks,” in G. Grindhammer (ed.) et al.: Proceedings of the Ringberg Workshop on New Trends in HERA Physics, Ringberg Castle, Tegernsee, Germany, October 2–7, 2005, hep-ph/0602128

[28] M. Nielsen, S.J. Brodsky, G.F. de Téramond, H.G. Dosch, F.S. Navarra and L. Zou, arXiv:1805.11567 [hep-ph]