Quark-diquark model description for double charm baryons

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Abstract We report here the mass spectrum and magnetic moments of ccq(q ∈ u, d, s) systems in the potential model framework by assuming the inter-quark potential as the colour coulomb plus power form with power index ν varying between 0.1 to 2.0. Here the two charm quarks are considered for the diquark states. The conventional one gluon exchange interaction has been employed to get the hyperfine and the fine structure between different states. We have predicted many low-lying states whose experimental verification can exclusively support the quark-diquark structure of the baryons.

Key words non-relativistic model, quark-diquark model, double charmed baryons

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1 Introduction

Baryons containing two heavy quarks are interesting systems to study the quark-diquark structure of baryons. Recently SELEX, the charm hadroproduction experiment at Fermilab, has reported a narrow state at 3.519 GeV in the double charm sector of baryons [1]. Though future experimental observations are awaited for further evidences of doubly charmed baryons. Looking into the recent interest in the double heavy flavour sector of baryons, we have made an attempt to study here the mass spectra and magnetic moments of ccq(q ∈ u, d, s) systems based on the quark-diquark picture within a non-relativistic potential scheme.

2 Theoretical methodology

The Hamiltonian of the baryon, in the diquark model, can be written in terms of diquark Hamiltonian plus quark-diquark Hamiltonian as [2]

$$H = H_{jk} + H_{i,jk}. \tag{1}$$

The diquark (jk) Hamiltonian and that of the relative motion of the diquark (jk) and the third quark (i) is described by

$$H_d = H_{jk} = \frac{p^2}{2m_{jk}} + V_{jk}(r_{jk}), \tag{2}$$

$$H_{i,d} = H_{i,jk} = \frac{q^2}{2m_{i,jk}} + V_{i,jk}(r_{i,jk}), \tag{3}$$

where, p and q are the relative momenta of the quarks within the diquark and within the quark-diquark systems respectively. The inter-quark potential (V_{jk}) and the quark-diquark potential $(V_{i,jk})$ are taken as the same colour coulomb plus power form,

$$V_{jk} = -\frac{2}{3}\alpha_s \frac{1}{r_{jk}} + b\, r_{jk}^{\nu}$$

and

$$V_{i,jk} = -\frac{4}{3}\alpha_s \frac{1}{r_{i,jk}} + b\, r_{i,jk}^{\nu}$$

respectively, with the same confinement strength b. Within the variational scheme with the hydrogenic trial wave-function, the spin average mass of the system (ie. without spin contribution) can be obtained as

$$M_{QQq} = \Sigma m_i + E(\bar{\mu}), \tag{4}$$

where, $E(\mu)$ is the total binding energy obtained from the Eqs. (2) and (3). The spin dependent in-

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teractions among the diquark and among the quark-diquark structure have been included perturbatively by considering the spin dependent potential provided by [3]. We have employed $m_u = m_d$ =322 MeV, m_s =510 MeV and m_c =1420 MeV for the present study. The potential strength(b) is fixed for each choices of ν so as to get the lowest di-charm state, $M_{\Xi_{cc}}$=3.520 GeV. The respective values of $b(\nu)$ are listed in Table 1. The computed masses of the di-charm baryons with different combinations of the di-quark and quark bound states are listed in Table 1 against the potential index ν. Other model predictions are also listed for comparison.

Table 1. The mass spectrum of Ξ_{cc} and Ω_{cc} Baryons.

	Masses of the double charm baryons in GeV								Others	
ν	0.1	0.3	0.5	0.7	1.0	1.3	1.5	2.0	[3]	[5]
b in GeV$^{\nu+1}\rightarrow$	0.203	0.152	0.116	0.088	0.06	0.04	0.03	0.015		
$(n_d l_d n_l l) J^P$										
Ξ_{cc}										
$(1S\ 1s)1/2^+$	3.520	3.520	3.520	3.520	3.520	3.520	3.520	3.520	3.478	3.620
$(1S\ 1s)3/2^+$	3.532	3.542	3.554	3.561	3.582	3.595	3.597	3.617	3.610	3.727
$(1P\ 1s)1/2^-$	3.579	3.621	3.656	3.678	3.718	3.739	3.822	3.868	3.702	3.838
$(2S\ 1s)1/2^+$	3.585	3.639	3.688	3.724	3.784	3.823	3.837	3.878	3.812	3.910
$(1P\ 1s)3/2^-$	3.591	3.646	3.696	3.734	3.798	3.843	3.862	3.920	3.834	3.959
$(1S\ 1p)1/2^-$	3.606	3.659	3.714	3.753	3.822	3.873	3.897	3.959	3.927	4.053
$(1S\ 1p)3/2'^-$	3.609	3.665	3.719	3.764	3.837	3.892	3.915	3.980	4.034	4.101
$(2S\ 1s)3/2^+$	3.596	3.659	3.719	3.768	3.847	3.903	3.929	3.998	3.944	4.027
$(1S\ 1p)3/2^-$	3.610	3.669	3.727	3.774	3.855	3.918	3.947	4.031	4.039	4.136
$(1S\ 1p)5/2^-$	3.612	3.671	3.730	3.780	3.863	3.929	3.959	4.047	4.047	4.155
$(1S\ 1p)1/2'^-$	3.613	3.673	3.734	3.786	3.872	3.941	3.974	4.070	4.052	4.196
$(1S\ 2s)1/2^+$	3.611	3.675	3.740	3.795	3.883	3.950	3.982	4.063	–	–
$(1S\ 2s)3/2^+$	3.617	3.690	3.767	3.836	3.952	4.049	4.098	4.231	–	–
Ω_{cc}										
$(1S\ 1s)1/2^+$	3.658	3.641	3.628	3.614	3.603	3.588	3.578	3.563	3.594	3.778
$(1S\ 1s)3/2^+$	3.679	3.674	3.672	3.671	3.670	3.668	3.662	3.662	3.730	3.872
$(1P\ 1s)1/2^-$	3.717	3.742	3.763	3.774	3.797	3.805	3.803	3.808	3.812	4.002
$(2S\ 1s)1/2^+$	3.723	3.760	3.795	3.820	3.863	3.889	3.896	3.922	3.925	4.075
$(1P\ 1s)3/2^-$	3.738	3.778	3.814	3.844	3.886	3.916	3.929	3.965	3.949	4.102
$(1S\ 1p)1/2^-$	3.775	3.817	3.853	3.882	3.930	3.964	3.978	4.021	4.050	4.208
$(2S\ 1s)3/2^+$	3.743	3.791	3.837	3.878	3.934	3.976	3.996	4.043	4.064	4.174
$(1S\ 1p)3/2'^-$	3.780	3.820	3.857	3.885	3.935	3.968	3.979	4.018	4.102	4.325
$(1S\ 1p)5/2^-$	3.780	3.822	3.860	3.890	3.941	3.978	3.991	4.037	4.134	4.303
$(1S\ 1p)1/2'^-$	3.782	3.824	3.865	3.896	3.951	3.990	4.005	4.050	4.145	4.252
$(1S\ 2s)1/2^+$	3.780	3.825	3.868	3.902	3.957	3.994	4.009	4.047	–	–
$(1S\ 1p)3/2^-$	3.783	3.827	3.870	3.903	3.962	4.005	4.023	4.079	4.176	4.271
$(1S\ 2s)3/2^+$	3.787	3.842	3.898	3.946	4.027	4.091	4.120	4.202	–	–

3 Magnetic moments of the double charm baryons

The magnetic moment of baryons are obtained in terms of the constituting quarks as [4]

$$\mu_B = \sum_i \langle \phi_{sf} \,|\, \mu_i \vec{\sigma}_i \,|\, \phi_{sf} \rangle , \tag{5}$$

where

$$\mu_i = \frac{e_i}{2m_i^{\rm eff}} . \tag{6}$$

Here, e_i, $m_i^{\rm eff}$ and σ_i represents the charge, effective mass and the spin of the quark constituting the baryonic state. $|\phi_{sf}\rangle$ represents the spin-flavour wave function of the respective baryonic state [4]. We consider the mass of bound quarks inside the baryons as its effective mass taking into account of its binding interactions with other two quarks. The effective mass for each of the constituting quark $m_i^{\rm eff}$ can be defined as [4]

$$m_i^{\rm eff}=m_i\left(1+\frac{E(\bar{\mu})}{\sum\limits_i m_i}\right) \tag{7}$$

such that the corresponding mass of the baryon is given by

$$M_{\rm B}=\sum_i m_i+E(\bar{\mu})=\sum_i m_i^{\rm eff}.$$

The magnetic moments of the ground state baryons containing double charm quarks predicted in the present study are listed in Table 2. Other theoretical model predictions of the magnetic moments are also listed for comparison.

Table 2. The magnetic moments of the $(1S\ 1s)$ $1/2^+$ and $(1S\ 1s)$ $3/2^+$ of $\Xi_{\rm cc}$ and $\Omega_{\rm cc}$ baryons (in $\mu_{\rm N}$) with the choice of ν in the range 0.1 to 2.0.

$\Xi_{\rm cc}$	-0.0548	-0.208[6]
$\Xi_{\rm cc}^*$	2.5298−2.4704	2.670[6]
$\Omega_{\rm cc}$	0.7251−0.7445	0.635[6]
$\Omega_{\rm cc}^*$	0.2429−0.2441	0.139[6]

4 Results and discussions

We have employed a simple nonrelativistic approach with coulomb plus power law interquark potential to study the masses of the double charm baryons in the quark-diquark model. The model parameters are obtained to get the ground state spin average masses of the ccq systems. The mass spectra and the magnetic moments of the ground states of $\Xi_{\rm cc}$ and $\Omega_{\rm cc}$ are listed in Table 1. Our predicted hyperfine splitting of the ground state $\frac{1}{2}^+$ and $\frac{3}{2}^+$ baryons fall in the range 10-100 MeV as ν changes from 0.1 to 2.0 with 62 MeV at $\nu=1.0$ as against the reported values of 76.6 MeV by lattice QCD [7], 130±30 MeV by potential models [3] and of 120±40 by QCDEFT [8]. We have predicted new lowlying states exclusively coming from diquark-quark structure of the double charm baryons. Our magnetic moment prediction for $\Xi_{\rm cc}$ is lower than the predicted value of -0.208 by the non-relativistic model, while other predictions of magnetic moments of $\Omega_{\rm cc}$, $\Omega_{\rm cc}^*$ and $\Xi_{\rm cc}^*$ are comparable with that of [6]. We look forward to the future experimental results in support of these baryonic properties before making further conclusions.

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