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Electromagnetic structure of charmed baryons

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We compute the electromagnetic form factors of charmed baryons (Σ_c, Ξ_{cc}, Ω_c and Ω_{cc}) in 2+1 Lattice QCD and extract their electric and magnetic charge radii as well as their magnetic moments. Such observables are important to understand the structure and the inner dynamics of the hadrons. We find that the existence of the heavy quarks drive the charge radii and magnetic moments to smaller values as compared to those of, e.g., proton.

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1. Introduction

Electromagnetic form factors are one of the probes to gain information about the inner structure of the hadrons, such as their sizes or distributions of their components. It is possible to determine these form factors starting form the perspective of the quark-gluon degrees of freedom in the framework of lattice QCD. In our previous works we have shown that the existence of a charm quark drives the charge radii and magnetic moments of the hadrons to smaller values [1, 2]. It has also been shown that the compactness of the Ξ_{cc} baryon [2] can be related to the large mass isospin splittings reported by the SELEX Collaboration and this might be an indication of a peculiar quark distribution within the baryon [3]. Yet it is interesting to see how the charge radii are affected as the light quark gets heavier. If the extra light quark decreases the string tension between the two-charm component [4], we shall expect an increase in the size of the hadron as this extra quark gets heavier. This is possible to test by replacing the u/d quark by an s quark.

In this work, we extend our previous work on the Ξ_{cc} baryon and report our preliminary results for the singly charmed $\Sigma_c^{(0,++)}(cuu,cdd)$, $\Omega_c^0(css)$ baryons and the doubly charmed $\Omega_{cc}^+(ccs)$ baryon. In particular we compute the electric and magnetic charge radii, and the magnetic moments of these baryons.

2. Lattice Formulation and Setup

The matrix element of the electromagnetic vector current is written as:

$$\langle B(p)|V_\mu|B(p')\rangle = \bar{u}(p)\left[\gamma_\mu F_{1,B}(q^2) + i\frac{\sigma_{\mu\nu}q^\nu}{2m_B}F_{2,B}(q^2)\right]u(p), \tag{2.1}$$

where $V_\mu = \sum_q e_q \bar{q}(x)\gamma_\mu q(x)$ and q runs over the quark content of the baryon. $q_\mu = p'_\mu - p_\mu$ is the transferred four-momentum. Here $u(p)$ denotes the Dirac spinor for the baryon with four-momentum p^μ and mass m_B. One can write the Sachs form factors, $G_B^{E,M}(q^2)$, as linear combinations of the Dirac and Pauli form factors, $F_{1,B}(q^2)$ and $F_{2,B}(q^2)$, which are related to the electric and magnetic form factors by

$$G_{E,B}(q^2) = F_{1,B}(q^2) + \frac{q^2}{4m_B^2}F_{2,B}(q^2), \quad G_{M,B}(q^2) = F_{1,B}(q^2) + F_{2,B}(q^2). \tag{2.2}$$

We follow the method in Ref.[5] to compute the Eq. 2.1. Using the following ratio

$$R(t_2,t_1;\mathbf{p}',\mathbf{p};\Gamma;\mu) = \frac{\langle F^{BV_\mu B'}(t_2,t_1;\mathbf{p}',\mathbf{p};\Gamma)\rangle}{\langle F^{BB}(t_2;\mathbf{p}';\Gamma_4)\rangle}\left[\frac{\langle F^{BB}(t_2-t_1;\mathbf{p};\Gamma_4)\rangle\langle F^{BB}(t_1;\mathbf{p}';\Gamma_4)\rangle\langle F^{BB}(t_2;\mathbf{p}';\Gamma_4)\rangle}{\langle F^{BB}(t_2-t_1;\mathbf{p}';\Gamma_4)\rangle\langle F^{BB}(t_1;\mathbf{p};\Gamma_4)\rangle\langle F^{BB}(t_2;\mathbf{p};\Gamma_4)\rangle}\right]^{1/2}, \tag{2.3}$$

where the $\langle F^{BV_\mu B'}(t_2,t_1;\mathbf{p}',\mathbf{p};\Gamma)\rangle$ and $\langle F^{BB}(t_2;\mathbf{p}';\Gamma_4)\rangle$ are baryonic two-point and three-point correlation functions respectively. $\Gamma = \gamma_4\gamma_5\Gamma_4$ for the electric and $\Gamma = \gamma_i\gamma_5\Gamma_4$ for the magnetic form factor with $\Gamma_4 \equiv (1+\gamma_4)/2$. t_1 is the time when the external electromagnetic field interacts with a quark and t_2 is the time when the final baryon state is annihilated. When $t_2 - t_1$ and $t_1 \gg a$, we extract the $G_{E,B}(q^2)$ and $G_{M,B}(q^2)$ as:

$$R(t_2,t_1;\mathbf{p}',\mathbf{p};\Gamma_4;\mu) \xrightarrow[t_2-t_1\gg a]{t_1\gg a} \Pi(\mathbf{0},-\mathbf{q};\Gamma_4;\mu=4) = \left[\frac{(E_B+m_B)}{2E_B}\right]^{1/2} G_{E,B}(q^2), \tag{2.4}$$

$$R(t_2,t_1;\mathbf{p}',\mathbf{p};\Gamma_i;\mu) \xrightarrow[t_2-t_1\gg a]{t_1\gg a} \Pi(\mathbf{0},-\mathbf{q};\Gamma_j;\mu=i) = \left[\frac{1}{2E_B(E_B+m_B)}\right]^{1/2} \varepsilon_{ijk}\, q_k\, G_{M,B}(q^2). \quad (2.5)$$

Once the form factor values are extracted for each Q^2 value they are fitted to the dipole form,

$$G_{E,M}(Q^2) = \frac{G_{E,M}(0)}{(1+Q^2/\Lambda^2_{E,M})^2}, \quad (2.6)$$

and the electric and magnetic charge radii are extracted via $\langle r^2_{E,M}\rangle = 12/\Lambda^2_{E,M}$. $G_M(0)$ is not accessible directly so we also determine the $G_M(0)$ from the fit and evaluate the magnetic moments by, $\mu_B = G_M(0)\,(m_N/m_B)\,\mu_N$ in nuclear magneton units, where m_N is the physical nucleon mass and m_B is the baryon mass as obtained on the lattice.

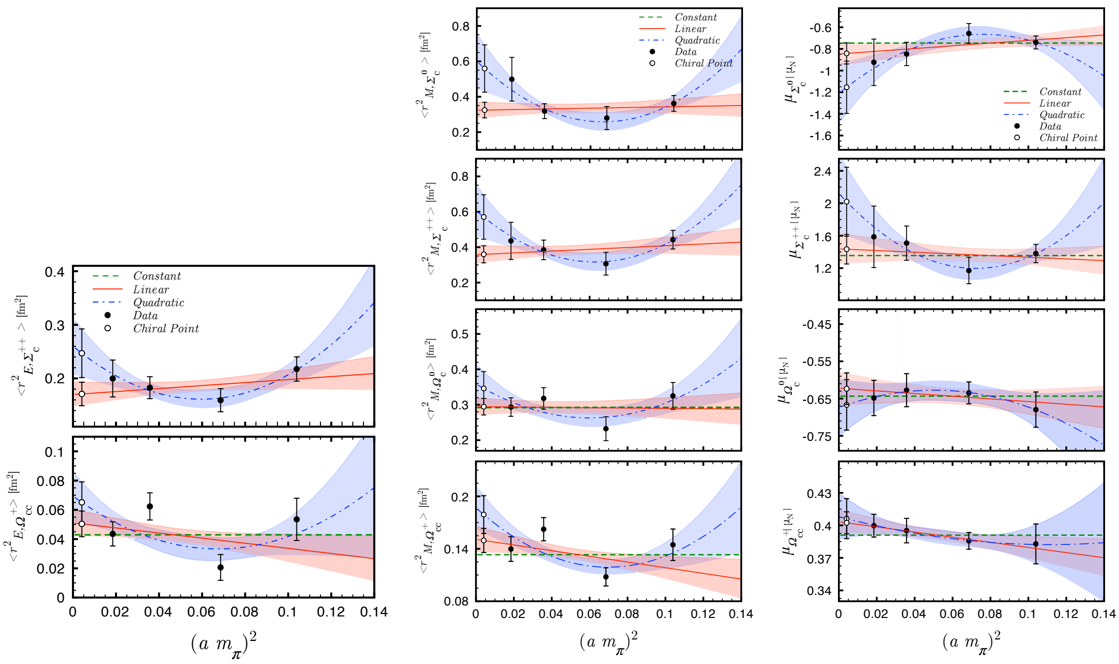
We use the $32^3\times 64$, $\beta = 1.9$, $2+1$-flavor configurations with four different light quark hopping parameters $\kappa^{u,d}_{sea} = 13700, 13727, 13754, 13770$, $\kappa^s_{sea} = 0.13640$ generated by the PACS-CS Collaboration [6]. Valence quark hopping parameters are taken as $\kappa^q_{sea} = \kappa^q_{val}$ and the clover action is employed. We chose the clover action for the charm quark also and fix the $\kappa_c = 0.1224$ so as to reproduce the mass of the J/ψ meson.

For each κ^{ud}_{sea} value, we perform our measurements on 100, 100, 150 and 170 different configurations for the Σ_c and 100, 100, 100 and 130 different configurations for the Ω_c and Ω_{cc} baryons. In order to increase the statistics for the Σ_c baryons , we have employed multiple source-sink pairs by shifting them 12 lattice units in the temporal direction while one pair have been enough for the others. We insert momentum through the current up to nine units: $(|p_x|,|p_y|,|p_z|)$=(0,0,0), (1,0,0), (1,1,0), (1,1,1), (2,0,0), (2,1,0), (2,1,1), (2,2,0), (2,2,1) and average over equivalent momenta. All statistical errors are estimated by the single-elimination jackknife analysis. We use the point-split lattice vector current, $V_\mu = [\overline{q}(x+\mu)U^\dagger_\mu(1+\gamma_\mu)q(x) - \overline{q}(x)U_\mu(1-\gamma_\mu)q(x+\mu)]/2$, since it does not need renormalisation.

3. Results and Conclusions

Here we discuss the chiral extrapolations only and refer the reader to Ref. [7] for the details of the plateau fits to Eq. 2.3 and form factor fits. In Table 1, we give the electric and magnetic charge radii in fm^2, and the magnetic moments (μ_B) in nuclear magnetons at the chiral point. These numerical values are illustrated in Figs. 1a, 1b, 1c with their chiral extrapolations. Results at each light quark kappa can be found in Ref. [7]. We used three fit forms that are constant, linear and quadratic in m^2_π as, $f_{con} = c$, $f_{lin} = am^2_\pi + b$, $f_{quad} = am^4_\pi + bm^2_\pi + c$, where a, b and c are the fit parameters.

Our findings indicate that the electric charge radii of Ω^+_{cc} and Ξ^+_{cc} [2] are about the same size but much smaller compared to that of the proton (the PDG value is $\langle r^2_{E,p}\rangle$ =0.770 fm^2 [8]). Electric charge radius seems to be insensitive to replacing the light d-quark by an s-quark. Σ^{++}_c baryon has the largest electric charge radius amongst the baryons that we considered. Magnetic charge radii also demonstrate a similar pattern as the electric charge radii. The magnetic charge radii of Σ^{++}_c and Σ^0_c are close to that of the proton's, which is $\langle r^2_{M,p}\rangle = 0.604$ fm^2 [8]. Electric and magnetic radii's light quark mass dependence is better modeled by a quadratic fit amongst the fit models that we considered and we have argued in Ref. [2] that such a behavior may be related to the



(a) (b) (c)

Figure 1: The chiral extrapolations for a) electric charge radii, b) magnetic charge radii, c) magnetic moments of Σ_c^0, Σ_c^{++}, Ω_c^0 and Ω_{cc}^+. We show the fits to constant, linear and quadratic forms. The shaded regions are the maximally allowed error regions for the fit forms.

Table 1: The electric and magnetic charge radii in fm^2, the values of magnetic form factors at $Q^2 = 0$ ($G_{M,B}(0)$), the magnetic moments in nuclear magnetons, for $B \equiv \Sigma_c^{++}$, Σ_c^0, Ω_{cc}, Ω_c at the chiral point. Charge radii and magnetic moments results are from quadratic and linear fits, respectively.

$\langle r^2_{E,\Sigma_c^{++}}\rangle$ [fm^2]	$\mu_{\Sigma_c^0}$ [μ_N]	$\mu_{\Sigma_c^{++}}$ [μ_N]	$\langle r^2_{M,\Sigma_c^0}\rangle$ [fm^2]	$\langle r^2_{M,\Sigma_c^{++}}\rangle$ [fm^2]
0.240(44)	-0.875(103)	1.499(202)	0.568(130)	0.656(142)
$\langle r^2_{E,\Omega_{cc}}\rangle$	μ_{Ω_c}	$\mu_{\Omega_{cc}}$	$\langle r^2_{M,\Omega_c}\rangle$	$\langle r^2_{M,\Omega_{cc}}\rangle$
0.064(15)	-0.627(43)	0.402(10)	0.343(52)	0.176(24)

confinement-force modification. In the case of Ω_c and Ω_{cc}, their electric and magnetic charge radii show unexpected light quark mass dependance since they do not contain light valence quarks. Such peculiarity remains as an open question. However, their magnetic moments are almost independent of the sea-quark effects. We fit the charge radii to a quadratic form since we expect the chiral point results for Ω_{cc}^+ and Ω_c^0 baryons to match the $\kappa_{u/d} \rightarrow \kappa_s$ results of Ξ_{cc}^+ and Σ_c^0 baryons and consider linear fit results for the magnetic moments. A detailed discussion can be found in Ref. [7].

An analysis of the individual quark contributions [7] shows that the c quark core shifts the centre of mass towards itself thus shrinking the baryon even though the light quark contributions are systematically larger. The charm quark contributions are independent of the quark content of the baryons and the contributions from the u/d- and s-quark are roughly the same, thus leading Σ_c^{++} and Ξ_{cc}^{++}, as well as, Ω_{cc}^{+} and Ξ_{cc}^{+} to have almost the same sizes.

Doubly represented quarks have the dominant contribution to the magnetic moments and the opposite signs of the light and heavy quark contributions suggest that their spins are generally anti-aligned within the baryon. Σ_c^{++} has the largest magnetic moment of all and the strange baryons Ω_c and Ω_{cc} have somewhat smaller moments. It is interesting to compare these values with the experimental magnetic moment of the proton, which is $\mu_p = 2.793\ \mu_N$ [8]. Comparing our magnetic moment results with several other models we see a quantitative disagreement even though the signs match [7].

In conclusion, we have extracted the electric and magnetic charge radii and the magnetic moments of the Σ_c, Ω_c, Ξ_{cc}, Ω_{cc} baryons from 2+1-flavor simulations of QCD on a $32^3 \times 64$ lattice. Our results imply that the charmed baryons are compact with respect to baryons that are composed of only light quarks, *e.g.*, the proton. The existence of the heavy quark shrinks the baryons and doubly charmed baryons are more compact than the singly charmed baryons of the same charge. The size of the baryon is increased when the u/d is replaced by the s quark in a qQQ system which might be due to the confinement dynamics. Ω_{cc} has the smallest and Σ_c^{++} and Σ_c^{0} baryons have larger and roughly the same magnetic radii. The magnetic moments are dominantly determined by the doubly represented quarks. The signs of the magnetic moments are correctly reproduced on the lattice. However, in general we see an underestimation of the magnetic moments as compared to what has been found with other theoretical methods. A work is underway with a redetermined κ_c and improved analysis.

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