Physics Letters B 754 (2016) 343–348

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

IR-improved soft-wall AdS/QCD model for baryons

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ARTICLE INFO

Article history:
Received 24 September 2015
Received in revised form 20 January 2016
Accepted 23 January 2016
Available online 25 January 2016
Editor: N. Lambert

ABSTRACT

We construct an infrared-improved soft-wall AdS/QCD model for baryons by considering the infrared-modified 5D conformal mass and Yukawa coupling of the bulk baryon field. The model is also built by taking into account the parity-doublet pattern for the excited baryons. When taking the bulk vacuum structure of the meson field to be the one obtained consistently in the infrared-improved soft-wall AdS/QCD model for mesons, we arrive at a consistent prediction for the baryon mass spectrum in even and odd parity. The prediction shows a remarkable agreement with the experimental data. We also perform a calculation for the $\rho(a_1)$ meson–nucleon coupling constant and obtain consistent result in comparison with the experimental data and other effective models.

1. Introduction

Quantum chromodynamics (QCD) is the fundamental theory describing the strong interactions among quarks and gluons. QCD has been successfully applied to study the perturbative effects of strong interactions at high energies due to the property of asymptotic freedom [1,2]. However, it is very hard to be used directly in the nonperturbative low-energy regime. Numerical methods or other effective theories have been constructed to give a low-energy description of the strong interaction, such as lattice QCD or chiral effective field theory [3,4]. The discovery of Anti-de Sitter/Conformal field theory (AdS/CFT) [5–7], which establishes the duality between the weak coupled supergravity in AdS_5 and the strong coupled $N = 4$ super Yang–Mills gauge theory in the boundary, provides new idea for solving the challenge problems of strong interaction at low energies. Based on AdS/CFT, a holographic description of QCD has been established. A number of researches have been focused on the low-energy phenomenology of hadrons. Many different models have been constructed, and they are usually called AdS/QCD or holographic QCD. Generally speaking, these models can be divided into top-down and bottom-up approaches. The former starts from certain brane configurations in string theory to reproduce some basic features of QCD [8–10]. The latter is constructed on the basis of low-energy properties of QCD, such as chiral symmetry breaking and quark confinement [11–13].

In the bottom-up approach, the hard-wall and soft-wall models are successful ones in describing hadron physics. The hard-wall model [11] used a sharp cut-off in the extra dimension to realize chiral symmetry breaking, while the linear Regge behavior of meson spectrum is lacking in this model. In the soft-wall model [12], an IR-suppressed dilaton term was added to reproduce the Regge behavior of mass spectrum, but the chiral symmetry breaking phenomenon cannot be consistently realized. Many efforts [14–18] have been made to build more realistic and predictive models, so that the mass spectrum of mesons can be matched up better in comparison with the experimental data. Some other characteristic quantities, such as interacting couplings or form factors, can also be produced well. In [18], we proposed a modified soft-wall AdS/QCD model which leads to a more consistent description for the mass spectrum of mesons.

Application of holographic QCD approach to baryons has also attracted much attention [19–29]. A number of quantities including the baryon spectrum and electromagnetic form factors of nucleons as well as the meson–nucleon couplings have been calculated in both hard-wall and soft-wall models. In [20], a hard-wall model for low-lying spin-$\frac{1}{2}$ baryons which includes the effects of chiral symmetry breaking was proposed to explain the parity-doublet pattern of excited baryons. Other models have also been constructed to tackle the problems of baryons in the soft-wall AdS/QCD framework [30,31]. However, it can be shown that there

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http://dx.doi.org/10.1016/j.physletb.2016.01.045

is a massless mode due to the lack of chiral symmetry breaking in these models.

In this paper, we shall pay attention to the infrared (IR) behavior of AdS/QCD model and build an IR-improved soft-wall AdS/QCD model for baryons with two light flavors. The model is constructed by considering the IR-modified conformal mass and Yukawa coupling of the bulk baryon field with the bulk meson field. To be consistent with the soft-wall AdS/QCD model for mesons, the vacuum structure for the bulk meson field is taken to be the same as the one obtained in the IR-improved soft-wall AdS/QCD model for mesons, which has been shown to provide a consistent prediction for the mass spectra of mesons [18]. In Sec. 2, the model is built by taking into account the parity-doublet pattern of excited baryons as discussed in the hard-wall baryon model [20]. As a consequence, we arrive at a more realistic IR-improved soft-wall AdS/QCD model for baryons. Such a model can provide a consistent prediction for the baryon mass spectrum which fits the experimental data very well. In Sec. 3, we calculate the $\rho(a_1)$ meson–nucleon coupling constant and compare our result with the ones obtained from the empirical estimation and other models. The conclusions and remarks are presented in Sec. 4.

2. Baryon mass spectrum in IR-improved soft-wall AdS/QCD model

2.1. Action of IR-improved soft-wall AdS/QCD model

Let us first construct the soft-wall AdS/QCD model for baryons. We use the standard 5D AdS space-time as the background:

$$ds^2 = e^{2A(z)}\left(\eta_{\mu\nu}dx^\mu dx^\nu - dz^2\right) \tag{1}$$

with $A(z) = -\ln z$ and $\eta^{\mu\nu} = \mathrm{diag}\{+1, -1, -1, -1\}$.

To consider the parity-doublet pattern of excited baryons, a pair of 5D spinors N_1 and N_2 corresponding to the spin-$\frac{1}{2}$ chiral baryon operators $\mathcal{O}_L$ and $\mathcal{O}_R$ in 4D should be introduced, as discussed in Ref. [20]. The chiral baryon operators $\mathcal{O}_L$ and $\mathcal{O}_R$ transform as $(2,1)$ and $(1,2)$ under $SU(2)_L \times SU(2)_R$ respectively. The bulk action of the Dirac fields N_j $(j = 1, 2)$ is constructed as follows

$$S_{N_j} = \int d^5x\sqrt{g}\left[\frac{i}{2}\bar{N}_j e^M_A \Gamma^A \nabla_M N_j - \frac{i}{2}(\nabla^\dagger_M \bar{N}_j) e^M_A \Gamma^A N_j \right. \\ \left. - \hat{m}_N(z)\delta_j \bar{N}_j N_j\right], \tag{2}$$

where $\Gamma^A = (\gamma^\mu, -i\gamma^5)$ are the 5D Dirac matrices which satisfy $\left\{\Gamma^A, \Gamma^B\right\} = 2\eta^{AB}$ with $\eta^{AB} = \mathrm{diag}\{+1, -1, -1, -1, -1\}$, e^M_A is the vielbein satisfying $g_{MN} = e^A_M e^B_N \eta_{AB}$, and ∇_M is the Lorentz and gauge covariant derivative

$$\nabla_M = \partial_M - \frac{i}{2}\omega^{AB}_M \Gamma_{AB} - i(A^a_L)_M t^a \tag{3}$$

with ω^{AB}_M the spin connection given by $\omega^{AB}_M = \partial_z A(z)(\delta^A_M \delta^B_z - \delta^A_z \delta^B_M)$ and $\Gamma^{AB} = \frac{i}{4}\left[\Gamma^A, \Gamma^B\right]$.

Unlike the usual soft-wall AdS/QCD model for mesons in which there is an explicit dilaton term in the bulk action, such an exponential term of dilaton for the spin-$\frac{1}{2}$ fermion case can be removed from the action by making a rescaling definition for the fermionic baryon fields [31]. $\hat{m}_N(z)$ is the IR-modified 5D conformal mass of the bulk spinors:

$$\hat{m}_N(z) = m_5 + \tilde{m}_N(z) \tag{4}$$

with m_5 the 5D conformal mass. The magnitude of m_5 is fixed by the general AdS/CFT relation with the scaling dimension Δ of the boundary operator [32,33]:

$$m_5^2 = \left(\Delta - \frac{d}{2}\right)^2, \quad \Delta = \frac{9}{2}. \tag{5}$$

Here we take $m_5 = \frac{5}{2}$ and introduce $\delta_j = \pm 1$ to yield the right chiral zero modes when matching N_j with the 4D chiral operators $\mathcal{O}_L$ and $\mathcal{O}_R$ [20]:

$$\delta_j = \begin{cases} 1, & j = 1 \\ -1, & j = 2 \end{cases}. \tag{6}$$

The IR-modified 5D mass term $\tilde{m}_N(z)$ is considered to have the following simple form

$$\tilde{m}_N(z) = \frac{\mu_g^2 z^2}{1 + \mu_g^2 z^2}\lambda_N, \tag{7}$$

which is required to be vanishing in the ultraviolet (UV) region $z \to 0$ and get a non-zero fixed value in the IR region $z \to \infty$ due to the QCD confining effect. Here μ_g is the energy scale characterizing the low energy QCD [18]. Note that such an IR behavior is different from a simple quadratic term appearing in [28,31].

Let us now construct the IR-modified Yukawa coupling term between the bulk spinors (N_1, N_2) and the bulk scalar field X. The 5D spinors N_1 and N_2 are dual to the spin-$\frac{1}{2}$ chiral baryon operators $\mathcal{O}_L$ and $\mathcal{O}_R$ in 4D respectively [20,21], and the 5D action of them has the following form

$$S_Y = \int d^5x\sqrt{g}\left[-y_N(z)(\bar{N}_1 X N_2 + \bar{N}_2 X^\dagger N_1)\right], \tag{8}$$

so that the resulting effective 4D Lagrangian possesses the chiral symmetry $SU(N_f)_L \times SU(N_f)_R$ with N_f the flavor number. Note that when the bulk vacuum expectation value (bVEV) of X breaks the chiral symmetry, it remains keeping a vector-like symmetry, i.e., $SU(N_f)_L \times SU(N_f)_R \to SU(N_f)_V$. The IR-modified Yukawa coupling $y_N(z)$ is assumed to have the following properties at UV and IR regions:

$$y_N(z)|_{z\to 0} \to 0; \qquad y_N(z)\langle X(z)\rangle|_{z\to\infty} \to z^2. \tag{9}$$

It will be shown that the S_Y term will lift the would-be massless ground state of baryons to a massive state and split the degenerate massive excitations into parity doublets, so that it can explain the experimental sign of the parity doubling pattern of excited baryons [34]. Note that the Yukawa coupling $y_N(z)$ is considered to be an IR-modified one which is different from the case in [20], and its form will be specified later as it is relevant to the bVEV of the bulk meson field.

The general action for the bulk baryon field is given by

$$S_N = S_{N_1} + S_{N_2} + S_Y. \tag{10}$$

We shall investigate the phenomena of resonance baryons based on the above action.

2.2. Bulk vacuum expectation value of scalar meson field

The 5D action of the meson sector in the original soft-wall model [12] is given as

$$S = \int d^5x\sqrt{g}e^{-\Phi(z)}\,\mathrm{Tr}\left[|DX|^2 - m_X^2|X|^2 - \frac{1}{4g_5^2}(F_L^2 + F_R^2)\right] \tag{11}$$

with $D^M X = \partial^M X - iA^M_L X + iXA^M_R$, $A^M_{L,R} = A^{M\,a}_{L,R} t^a$ and $\mathrm{Tr}[t^a t^b] = \delta^{ab}/2$. The mass of the bulk scalar field X can be determined as $m_X^2 = -3$ by the standard AdS/CFT dictionary [7], and the gauge coupling g_5 is fixed to be $g_5^2 = 12\pi^2/N_c$ with N_c the color number [11]. The complex bulk field X is in general decomposed into the scalar and pseudoscalar mesons, and the chiral gauge fields A_L and A_R are identified to the vector and axial-vector mesons.

The bVEV of the scalar meson field X in the two-flavor case has the form as follows

$$\chi(z) \equiv \langle X \rangle = \frac{1}{2} v(z) \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \tag{12}$$

which satisfies the equation of motion derived from the action (11):

$$v''(z) + (3A'(z) - \Phi'(z))\, v'(z) - m_X^2\, e^{2A(z)}\, v(z) = 0\,. \tag{13}$$

As expected from the AdS/CFT dictionary [7], the bVEV $v(z)$ has the following behavior in the UV region $z \to 0$:

$$v(z \to 0) = m_q\, \zeta\, z + \frac{\sigma\, z^3}{\zeta}\,, \tag{14}$$

where m_q and σ are the current quark mass and quark condensate, respectively, and $\zeta = \sqrt{3}/(2\pi)$ is the normalization parameter [35].

In the original soft-wall model [12], $v(z)$ can be calculated from Eq. (13), but the solution will reach to a constant in the IR limit $z \to \infty$. Such an asymptotic behavior leads to the chiral symmetry restoration which is not supported in QCD [36]. In the recent studies [15,16,18], the IR asymptotic behavior of $v(z)$ is assumed to have a reliable form which can realize the chiral symmetry breaking. The simplest forms for the dilaton profile, the metric or the conformal mass have been modified in the IR region to make Eq. (13) consistent.

As shown in Ref. [18], a consistent IR-improved soft-wall AdS/QCD model for mesons with the quartic interaction term of bulk scalar field can be written as

$$S = \int d^5x \sqrt{g} e^{-\Phi(z)}\, \mathrm{Tr}\Big[|DX|^2 - m_X^2(z)|X|^2 - \lambda_X(z)|X|^4 - \frac{1}{4g_5^2}(F_L^2 + F_R^2) \Big], \tag{15}$$

where the conformal mass $m_X(z)$ and the quartic coupling $\lambda_X(z)$ are considered to have the proper IR-improved forms. The bVEV $v(z)$ has the following IR behavior

$$v(z \to \infty) = v_q z \tag{16}$$

with v_q the constant parameter which characterizes the energy scale of dynamically generated spontaneous chiral symmetry breaking caused by the quark condensate [4]. A simply parameterized form of $v(z)$ is taken as [18]

$$v(z) = \frac{Az + Bz^3}{1 + Cz^2} \tag{17}$$

with

$$A = m_q\zeta, \quad B = \frac{\sigma}{\zeta} + m_q\zeta C, \quad C = \mu_c^2/\zeta, \quad v_q = B/C, \tag{18}$$

where the constant parameter μ_c characterizes the QCD confinement scale.

Then we specify the Yukawa coupling $y_N(z)$ in action (8) as

$$y_N(z) = \lambda_A\, \mu_g z \left(1 - \lambda_B\, \mu_g^2 z^2 e^{-\mu_g^2 z^2}\right), \tag{19}$$

which is required to realize a consistent mass spectrum of resonance baryons compared with experimental data.

2.3. Equation of motion and solutions for parity-doublet baryons

Let us decompose the bulk baryon fields N_j $(j = 1, 2)$ into the chiral form

$$N_j = N_{jL} + N_{jR}, \tag{20}$$

where $i\Gamma^5 N_{jL} = N_{jL}$ and $i\Gamma^5 N_{jR} = -N_{jR}$. Then a KK decomposition for $N_{jL,R}$ is performed to yield the following form

$$N_{jL,R}(x, z) = \sum_n \int \frac{d^4p}{(2\pi)^4} e^{-ipx} f_{jL,R}^{(n)}(z) \psi_{L,R}^{(n)}(p)\,, \tag{21}$$

where $\psi_{L,R}^{(n)}(p)$ is the 4D spinors which satisfy $\gamma^5 \psi_L^{(n)}(p) = \psi_L^{(n)}(p)$, $\gamma^5 \psi_R^{(n)}(p) = -\psi_R^{(n)}(p)$ and $\not{p}\psi_{L,R}^{(n)}(p) = |p|\psi_{R,L}^{(n)}(p)$.

From the action given in Eq. (10), we can derive the equation of motion in terms of $f_{jL,R}$ $(j = 1, 2)$ as (note that we shall neglect the superscript of $f_{jL,R}^{(n)}$ and $\psi_{L,R}^{(n)}$ below for convenience)

$$\begin{aligned}
&\begin{pmatrix} \partial_z - e^{A(z)}\, \hat{m}_N(z) + \frac{d}{2} A'(z) & -y_N\, e^{A(z)}\, \chi(z) \\ -y_N\, e^{A(z)}\, \chi(z) & \partial_z + e^{A(z)}\, \hat{m}_N(z) + \frac{d}{2} A'(z) \end{pmatrix} \begin{pmatrix} f_{1L} \\ f_{2L} \end{pmatrix} \\
&\quad = -|p| \begin{pmatrix} f_{1R} \\ f_{2R} \end{pmatrix} \\
&\begin{pmatrix} \partial_z + e^{A(z)}\, \hat{m}_N(z) + \frac{d}{2} A'(z) & y_N\, e^{A(z)}\, \chi(z) \\ y_N\, e^{A(z)}\, \chi(z) & \partial_z - e^{A(z)}\, \hat{m}_N(z) + \frac{d}{2} A'(z)) \end{pmatrix} \begin{pmatrix} f_{1R} \\ f_{2R} \end{pmatrix} \\
&\quad = |p| \begin{pmatrix} f_{1L} \\ f_{2L} \end{pmatrix}.
\end{aligned} \tag{22}$$

Here we need to clarify the even and odd parity of baryons, which is hidden in the above equation of motion. The parity transformations of 4D spinors $\psi_{L,R}$ are defined as (P is a unitary representation of parity transformation)

$$P^{-1}\psi_{L,R}(x)P = \gamma^0 \psi_{R,L}(\bar{x}) \tag{23}$$

with $\bar{x} = (t, -\vec{x})$. The parity transformation for the 5D spinors are defined as

$$\begin{aligned}
&P^{-1}N_{1L}(x,z)P = \eta_1\gamma^0 N_{2R}(\bar{x},z), \\
&P^{-1}N_{1R}(x,z)P = \eta_2\gamma^0 N_{2L}(\bar{x},z), \\
&P^{-1}N_{2L}(x,z)P = \eta_2\gamma^0 N_{1R}(\bar{x},z), \\
&P^{-1}N_{2R}(x,z)P = \eta_1\gamma^0 N_{1L}(\bar{x},z).
\end{aligned} \tag{24}$$

It is easy to prove that the action (10) is parity invariant if η_1, η_2 satisfy the relations [30,37]:

$$\eta_1^*\eta_1 = \eta_2^*\eta_2 = 1, \quad \eta_1^*\eta_2 = \eta_2^*\eta_1 = -1\,. \tag{25}$$

For convenience, we restrict η_1 and η_2 to be real. We will show that $\eta_1 = 1, \eta_2 = -1$ correspond to the even parity case, while $\eta_1 = -1, \eta_2 = 1$ correspond to the odd parity case. Using Eqs. (23) and (24), we can easily find the relations between the bulk profiles $f_{jL,R}$ $(j = 1, 2)$ corresponding to the even and odd parity, respectively:

$$\begin{aligned}
&f_{1L}(z) = f_{2R}(z), \quad f_{1R}(z) = -f_{2L}(z) \qquad \text{even}, \\
&f_{1L}(z) = -f_{2R}(z), \quad f_{1R}(z) = f_{2L}(z) \qquad \text{odd}.
\end{aligned} \tag{26}$$

Now we introduce $f_j^+(z)$ and $f_j^-(z)$ with the forms as follows

$$\begin{aligned}
&f_1^+(z) = f_{1L}(z) + f_{2R}(z), \qquad f_2^+(z) = f_{1R}(z) - f_{2L}(z), \\
&f_1^-(z) = f_{1L}(z) - f_{2R}(z), \qquad f_2^-(z) = f_{1R}(z) + f_{2L}(z).
\end{aligned} \tag{27}$$

Table 1
The values of input parameters. m_q, σ, μ_g, μ_c are taken from [18].

m_q (MeV)	$\sigma^{1/3}$ (MeV)	μ_g (MeV)	μ_c (MeV)	λ_A	λ_B	λ_N
3.52	290	473	375	3.93	16.58	2.55

Then Eq. (22) can be decoupled as

$$\begin{pmatrix} -\partial_z + e^{A(z)}\hat{m}_N(z) - \frac{d}{2}A'(z) & -y_N\, e^{A(z)}\chi(z) \\ y_N e^{A(z)}\chi(z) & \partial_z + e^{A(z)}\hat{m}_N(z) + \frac{d}{2}A'(z) \end{pmatrix} \begin{pmatrix} f_1^+ \\ f_2^+ \end{pmatrix} = |p| \begin{pmatrix} f_2^+ \\ f_1^+ \end{pmatrix}, \tag{28}$$

$$\begin{pmatrix} -\partial_z + e^{A(z)}\hat{m}_N(z) - \frac{d}{2}A'(z) & y_N\, e^{A(z)}\chi(z) \\ -y_N\, e^{A(z)}\chi(z) & \partial_z + e^{A(z)}\hat{m}_N(z) + \frac{d}{2}A'(z) \end{pmatrix} \begin{pmatrix} f_1^- \\ f_2^- \end{pmatrix} = |p| \begin{pmatrix} f_2^- \\ f_1^- \end{pmatrix}. \tag{29}$$

From Eqs. (26) and (27), we can see that for the even parity case only f_j^+ $(j = 1, 2)$ survive and for the odd parity case only f_j^- $(j = 1, 2)$ survive. f_j^+ and f_j^- are just the holographic analogues of the even and odd parity baryon wave functions, respectively.

2.4. Numerical results

As is noted above, in this paper we only consider the two-flavor case with lightest quarks u and d, and ignore the isospin symmetry breaking. The model involves seven parameters, i.e., m_q, σ, μ_g, μ_c, λ_N, λ_A and λ_B, and four of them appear in the IR-improved soft-wall AdS/QCD model for mesons [18], i.e., quark mass m_q, quark condensate σ, energy scales μ_c and μ_g. Here we just use the values of the four parameters obtained from [18] as it has been shown to provide a consistent prediction for the mass spectra of scalar, pseudoscalar, vector and axial-vector mesons. Thus there are only three parameters λ_N, λ_A and λ_B in the IR-improved soft-wall AdS/QCD model for baryons. We fit these three parameters by requiring the masses of the first three low-lying baryons with even parity to match the experimental value. Especially, the mass of nucleons is fixed to be 939 MeV. After fixing all the parameters, the masses of odd-parity baryons and the ones of the high excited states of even-parity baryons could be considered as our model prediction. The values of these parameters are shown in Table 1.

The baryon masses can be calculated by solving Eqs. (28) and (29) numerically with the boundary conditions $f_1^+(z \to 0) = f_2^+(z \to 0) = 0$ and $f_1^-(z \to 0) = f_2^-(z \to 0) = 0$. The results are presented in Tables 2 and 3, and the baryon wave functions are plotted in Fig. 1. One can see a good agreement between the theoretical calculations and the experimental values, and the results are much better than the hard-wall calculations in [20].

Table 2
Mass spectra of even-parity nucleons. The superscript $*$ represents the existence confidence level. The experimental data are from [38].

N (even)	0	1	2	3	4	5
Exp. (MeV)	939****	1440****	1710***	1880**	2100*	2300**
Theory (MeV)	939	1435	1698	1915	2105	2276

Table 3
Mass spectra of odd-parity nucleons. The superscript $*$ represents the existence confidence level. The experimental data are from [38].

N (odd)	0	1	2	3	4
Exp. (MeV)	1535****	1650****	1895**	–	–
Theory (MeV)	1473	1717	1927	2113	2281

3. (Axial-)vector meson–nucleon couplings

It is useful to apply the IR-improved AdS/QCD model for baryons described above to calculate the $\rho(a_1)$ meson–nucleon couplings, which can be compared with results in other models and empirical estimation from related experimental measurements. The vector meson–nucleon coupling constant has been calculated in the top-down models [39–41] and in the hard-wall models [42,43]. There are also some other calculations outside the holographic framework [44,45] and experimental estimations [46–49].

As was shown in [43,50], the vector–nucleon couplings may receive contributions in two ways. The first one comes from the gauge interactions which is incorporated in the covariant derivative of kinetic term of the action (2),

$$S^{gauge} = \int d^5x\sqrt{g}\,\Big[\frac{i}{2}\bar{N}_1 e_A^M \Gamma^A(-iA_M^L)N_1 - \frac{i}{2}((-iA_M^L)N_1)^\dagger \Gamma^0 e_A^M \Gamma^A N_1 + \frac{i}{2}\bar{N}_2 e_A^M \Gamma^A(-iA_M^R)N_2 - \frac{i}{2}((-iA_M^R)N_2)^\dagger \Gamma^0 e_A^M \Gamma^A N_2\Big]$$

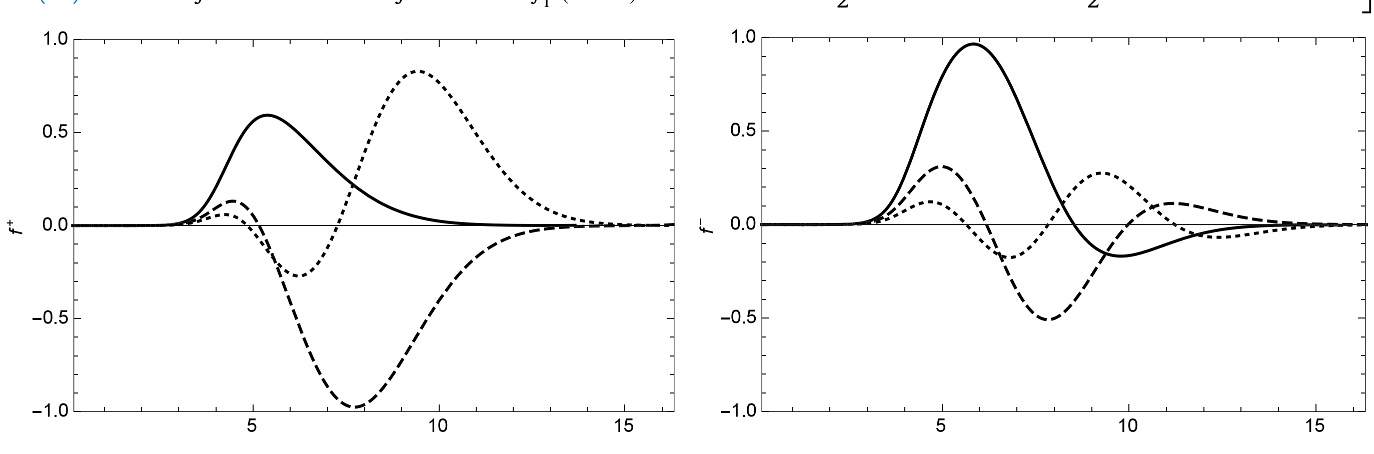

Fig. 1. Baryon wave functions for the first three even-parity states (left) and odd-parity states (right). The solid line represents ground states. The dashed line represents first excited states. The dotted line represents second excited states.

$$\supset \int d^4x \int_0^\infty \frac{dz}{z^4} \big[\bar{N}_1\gamma^\mu V_\mu N_1 + \bar{N}_2\gamma^\mu V_\mu N_2 + \bar{N}_1\gamma^\mu A_\mu N_1 - \bar{N}_2\gamma^\mu A_\mu N_2\big]$$
$$= \int d^4x \int_0^\infty \frac{dz}{z^4} \Big[V_0(z)(|f_{1L}^{(0)}(z)|^2 + |f_{2L}^{(0)}(z)|^2)\bar{\psi}\gamma^\mu V_\mu(x)\psi - A_0(z)(|f_{1L}^{(0)}(z)|^2 - |f_{2L}^{(0)}(z)|^2)\bar{\psi}\gamma^5\gamma^\mu A_\mu(x)\psi\Big]. \quad (30)$$

The second one originates from the Pauli term which was introduced in [50] for the evaluation of the anomalous magnetic dipole moment μ_{ano} and the CP-violating electric dipole moment d_e,

$$S^{Pauli} = i\kappa \int d^5x\sqrt{g}e_A^M e_B^N \Big[\bar{N}_1\Gamma^{AB}(F_L)_{MN}N_1 - \bar{N}_2\Gamma^{AB}(F_R)_{MN}N_2\Big]$$
$$\supset i\kappa \int d^5x\sqrt{g}z^2 \big[\bar{N}_{1L}\Gamma^{\mu z}(F_V)_{\mu z}N_{1L} + \bar{N}_{1R}\Gamma^{\mu z}(F_V)_{\mu z}N_{1R} - (1\leftrightarrow 2)\big]$$
$$+ i\kappa \int d^5x\sqrt{g}z^2 \big[\bar{N}_{1L}\Gamma^{\mu z}(F_A)_{\mu z}N_{1L} + \bar{N}_{1R}\Gamma^{\mu z}(F_A)_{\mu z}N_{1R} + (1\leftrightarrow 2)\big]$$
$$= -2\kappa \int d^4x \int_0^\infty \frac{dz}{z^3} \Big[V_0'(z)(|f_{1L}^{(0)}(z)|^2 - |f_{2L}^{(0)}(z)|^2)\bar{\psi}\gamma^\mu V_\mu(x)\psi - A_0'(z)(|f_{1L}^{(0)}(z)|^2 + |f_{2L}^{(0)}(z)|^2)\bar{\psi}\gamma^5\gamma^\mu A_\mu(x)\psi\Big]. \quad (31)$$

We can easily read the $\rho(a_1)$ meson–nucleon coupling constants from the above two formulas:

$$g_{\rho NN} = g_{\rho NN}^{(0)} + g_{\rho NN}^{(1)} = \int_0^\infty \frac{dz}{z^4} V_0(z)\,(|f_{1L}^{(0)}(z)|^2 + |f_{2L}^{(0)}(z)|^2) - 2\kappa \int_0^\infty \frac{dz}{z^3} V_0'(z)\,(|f_{1L}^{(0)}(z)|^2 - |f_{2L}^{(0)}(z)|^2), \quad (32)$$

and

$$g_{a_1 NN} = g_{a_1 NN}^{(0)} + g_{a_1 NN}^{(1)} = \int_0^\infty \frac{dz}{z^4} A_0(z)\,(|f_{1L}^{(0)}(z)|^2 - |f_{2L}^{(0)}(z)|^2) - 2\kappa \int_0^\infty \frac{dz}{z^3} A_0'(z)\,(|f_{1L}^{(0)}(z)|^2 + |f_{2L}^{(0)}(z)|^2). \quad (33)$$

Note that there are some differences of the above formulas from that in [43] though we follow the same procedure with the same action terms. The normalized wave function $(A_0)V_0$ of $(a_1)\rho$ meson has been determined in the IR-improved AdS/QCD model for mesons [18], and κ is fixed by the anomalous magnetic dipole moments of nucleons [50] as follows

$$\mu_{ano} = -e\,2\kappa \int_0^\infty \frac{dz}{z^3} f_{1L}^{(0)}(z) f_{2L}^{(0)}(z) \simeq \frac{1.8e}{2m_N} \quad (34)$$

with the nucleon mass $m_N \simeq 0.939$ GeV. Then we obtain $\kappa \simeq 0.19$ from Eq. (34).

Table 4
The values of $\rho(a_1)$ meson–nucleon coupling constants calculated in our model and other ones or estimated from experiments.

Model/Experiment	$g_{\rho NN}$	$g_{a_1 NN}$
Our model	2.48	0.14
Experiment [46–48]	$4.2 \sim 6.5$	–
Experiment [49]	2.52 ± 0.06	–
Sum rule [44]	-2.5 ± 1.1	–
Chiral quark [45]	2.8	–
Hard-wall [43]	$0.2 \sim 0.5$	$1.5 \sim 4.5$
Hard-wall [42]	−3.42 (−8.6)	–
Soft-wall [51]	5.33 (6.78)	–

Taking the parameters obtained in the IR-improved AdS/QCD model for mesons [18] and the IR-improved AdS/QCD model for baryons in this paper, we are able to calculate the $\rho(a_1)$ meson–nucleon coupling constant. The results are shown in Table 4 in comparison with other models or empirical values. [46–49] are empirical estimations from different experimental data, and [44] is QCD sum rule calculation. The result of [45] was obtained in the chiral quark model. [42,43] are hard-wall models with different action terms. [51] studied ρ meson–nucleon coupling constant in a soft-wall AdS/QCD model which is different from ours. In our calculation, the ρ and a_1 meson–nucleon couplings include two parts both from the gauge interaction terms and from the Pauli action terms. The numerical results from different terms are: $g_{\rho NN}^{(0)} \simeq 2.71$, $g_{\rho NN}^{(1)} \simeq -0.23$, $g_{a_1 NN}^{(0)} \simeq 0.29$, $g_{a_1 NN}^{(1)} \simeq -0.15$. It can be seen that the gauge interactions give the main contribution of the couplings, while the Pauli term contributes to a small negative part. From Table 4 we see that our result of $g_{\rho NN}$ is consistent with the ones from experiments and other effective models, yet the baryon spectrum in our model is reproduced much better than that in the hard-wall model [20], as has been shown in Tables 2 and 3.

4. Conclusions and remarks

We have built an IR-improved soft-wall AdS/QCD model for baryons. Two bulk spin-$\frac{1}{2}$ fermion fields and a bulk scalar field have been introduced as the basic block of this model, following [20]. The Yukawa coupling term in the action is necessary for inducing the chiral symmetry breaking, which is crucial for the mass of lowest-lying baryons, and splitting the baryons into a parity-doublet pattern of resonance states. The IR-modified 5D conformal mass $\tilde{m}_N(z)$ plays the role of an effective confining potential for attaining the reliable mass spectrum of baryons. By adopting the parameterization of the bVEV of bulk scalar field in the IR-improved soft-wall AdS/QCD model for mesons [18], we have arrived at a consistent mass spectrum of baryons, which agrees well with the experimental data. It has been shown that the combined behavior of the bVEV of bulk scalar field and the IR-modified Yukawa coupling $y_N(z)$ is critical for yielding the consistent mass spectra of the highly excited baryon states.

The (axial-)vector meson–nucleon coupling constants $g_{\rho NN}$ and $g_{a_1 NN}$ have been calculated within the IR-improved AdS/QCD model for baryons. We have considered both the gauge interaction term contained in the covariant derivative of action (2) and the terms related to the anomalous magnetic dipole moment of nucleons [43,50]. The numerical result of $g_{\rho NN} \simeq 2.48$ is consistent with the experimental data and other models of QCD. The coupling $g_{a_1 NN}$ has no experimental data, and our calculated value is much smaller than the one obtained in the hard-wall model [43] though the same action terms have been taken. Note that the formulas of $g_{\rho NN}$ and $g_{a_1 NN}$ are different from those in [43].

In this paper we have carried out the calculations for the mass spectrum of baryons in the two-flavor case and discussed the (axial-)vector meson–nucleon coupling constants. In general, many other properties relevant to baryons can be studied within the framework of the IR-improved AdS/QCD model for baryons, such as the nucleon electromagnetic and gravitational form factors, and the pion–nucleon coupling, etc. In particular, by considering the explicit chiral symmetry breaking due to quark masses, the three-flavor case which incorporates the baryon octet may be an interesting extension to be studied in the future.

Acknowledgements

This work was supported in part by the National Science Foundation of China (NSFC) under Grant Nos. 11475237, 11121064, 10821504 and also by the CAS Center for Excellence in Particle Physics (CCEPP).

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