Structure of heavy baryons in a pion mean-field approach

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(Received January 18, 2019)

In this talk, we briefly review a series of recent works on singly heavy baryons, based on a pion mean-field approach. In the limit of the infinitely heavy quark mass, heavy baryons are governed mainly by the light degrees of freedom. Taking the number of colors to be infinity, a heavy baryon arises as a state consisting of $N_c - 1$ valence quarks bound by the pion mean fields created self-consistently. Within this framework, we present the results of the mass spectra of the charmed and bottom baryons, and their magnetic moments. The behavior of the electromagnetic form factors will be also mentioned.

KEYWORDS: Singly-heavy baryons, pion mean-field approach, chiral quark-soliton model, electromagnetic properties of singly heavy baryons, strong decays of singly heavy baryons

1. Introduction

Mean-field approaches have been very successfully applied in physics. There are several examples: Nuclear shell models, Ginzburg-Landau theory for superconductivity, and quark potential models, to name a few. Witten showed that when the number of colors goes to infinity ($N_c \to \infty$), the mass of the nucleon is proportional to $N_c$ whereas its decay is of order $O(1)$ [1]. It implies that mesons are weakly interacting in the large $N_c$. This allows one to neglect the meson fluctuations. In this picture, the nucleon can be viewed as a bound state of $N_c$ valence quarks in a pion mean field. The presence of the $N_c$ valence quarks create an effective pion mean field that stems from the vacuum polarization. The $N_c$ valence quarks are then influenced by the mean field in a self-consistent manner.

The chiral quark-soliton model ($\chi$QSM) was constructed as a pion mean-field approach [2, 3]. The model has described various properties of the lowest-lying SU(3) light baryons successfully. The $\chi$QM can be also applied to the lowest-lying singly heavy baryons [4, 6, 7] (see also a recent review [5]). In the limit of the infinitely massive heavy quark ($m_Q \to \infty$), a singly heavy quark can be considered as a bound state of $N_c - 1$ valence quarks while the heavy quark is regarded as a mere static color source. In the present talk, we briefly report results of a series of recent works on various properties of the singly heavy baryons. The detailed formalism will not be discussed. They can be found in Refs. [5–7]. The results for the electric form factors of the heavy baryons show that their electromagnetic sizes more compact than those of the SU(3) hyperons [11].

2. Mass spectra of the lowest-lying singly heavy baryons

In Table I, we list the results of the charmed and bottom baryons with the second-order corrections of the flavor SU(3) symmetry breaking [7]. While all the dynamical parameters were computed self-consistently within the model, the hyperfine interactions, which bring about the splitting between the two sextet representations with spin $1/2$ and $3/2$, were introduced by hand as done in Ref. [6].
Table I. Results of the masses of the singly heavy baryon masses in unit of MeV. In the third and fourth columns, those of the charmed baryons and the corresponding experimental data are listed respectively, whereas the fifth and last columns represent the masses of the bottom baryons and corresponding experimental data, respectively. Note that the mass of the $\Omega_c^*$ in the $6_{3/2}$ representation is the prediction from the present model.

| $^{R_Q}_{J_B}$ | $B_Q$ | Charmed baryons | Experiment [8] | Bottom baryons | Experiment [8] |
|----------------|------|-----------------|----------------|----------------|----------------|
| $3_{1/2}$     | $\Lambda_Q$ | 2280.7          | 2286.5±0.1     | 5609.0         | 5615.9±0.2     |
| $3_{1/2}$     | $\Xi_Q$    | 2475.2          | 2469.4±0.3     | 5803.6         | 5793.1±0.7     |
| $6_{1/2}$     | $\Sigma_Q$ | 2576.8          | 2576.8±2.1     | 5933.8         | 5935.0±0.05    |
| $6_{1/2}$     | $\Omega_Q$ | 2700.1          | 2695.2±1.7     | 6057.1         | 6048.0±1.9     |
| $6_{3/2}$     | $\Sigma_Q^*$| 2645.0          | 2645.9±0.4     | 5958.6         | 5955.3±0.1     |
| $6_{3/2}$     | $\Omega_Q^*$| 2768.3          | 2765.9±2.0     | 6081.9         | 6079.0±1.3     |

The results are in good agreement with the experimental data [8]. The mass of the $\Omega_c^*$ with spin $3/2$ has not been measured, so the result is the prediction: $m^{(3/2)}_{\Omega_c^*} = 6081.9$ MeV. The present value is slightly smaller than $m^{(3/2)}_{\Omega_c^*} = 6095.0 \pm 4.4$ MeV that was obtained in the same model but in a model-independent manner [6].

In addition to the mass spectra of the baryon antitriplet and sextet, we also considered the baryon antidecapentaplet ($\bm{15}$) in the context of recent findings of the excited $\Omega_c$’s by the LHCb Collaboration [9]. Within the present framework, we favor the two excited $\Omega_c$’s with narrower widths as the members of the baryon antidecapentaplet, whereas the other $\Omega_c$’s as those of the excited baryon sextet. The detailed discussions can be found in Refs. [10, 12]. Note that the $\Omega_c$’s belonging to $\bm{15}$ are isotriplet states. It implies that if they are indeed in the isotriplet states, then a finding of charged $\Omega_c$’s is expected, which can be determined by the LHCb experiment.

3. Magnetic moments of the baryon sextet

The magnetic moments of the singly heavy baryons are also computed within the present scheme. Since the mass of the heavy quark is assumed to infinitely heavy, we can ignore a tiny contribution from the heavy quarks to them. Thus, the light quarks again govern the electromagnetic structure of the heavy baryons. We want to emphasize that all the relevant dynamical parameters have been already fixed by using the experimental data on the magnetic moments of the baryon octet.

As listed in Table II, the results of the charmed baryons are in qualitative agreement with the lattice data [13, 14]. As for the $\mu$ of the charmed baryons with spin $3/2$, there is only one data from lattice QCD. The magnitude of the present result for $\mu_{\Omega_c^*}$ is approximately 60 % larger than the lattice data. The reason can be found that the corrections from the charm quark are sizable in this case, which were ignored in the present work. Thus, it one needs to go beyond the mean-field approximation to carry out more quantitative calculations, taking into account $1/m_Q$ corrections. For the detailed discussion, we refer to a recent work [16].

4. Strong decays of the baryon sextet

It is also of great importance to compute the strong decays of the singly heavy baryons, since they give essential information on the structure of them. In the present approach, all the necessary dynamical parameters for the strong decays were already derived by using the SU(3) hyperon semileptonic decay constants [17]. Thus, we can straightforwardly obtain the results of the strong decay widths of
the singly heavy baryons without introducing any additional parameters.

Table II. Numerical results of the magnetic moments for the charmed baryon sextet with spin 1/2 and 3/2 in units of the nuclear magneton $\mu_N$. In the second and third columns, those of the charmed baryons and the corresponding lattice data are listed respectively, whereas the fifth and last columns represent those of the bottom baryons and corresponding lattice data, respectively. The lattice data are taken from Refs. [13–15].

| decay modes | this work | experiment |
|-------------|-----------|------------|
| $\Sigma_c^+$ | $1.93$ | $1.89^{+0.09}_{-0.18}$ |
| $\Sigma_c^+$ | $1.90$ | $1.83^{+0.11}_{-0.19}$ |
| $\Sigma_c^+$ | $14.47$ | $14.78^{+0.30}_{-0.19}$ |
| $\Sigma_c^+$ | $15.02$ | $<17$ |
| $\Sigma_c^+$ | $14.49$ | $15.3^{+0.04}_{-0.05}$ |
| $\Sigma_c^+$ | $14.49$ | $15.3^{+0.04}_{-0.05}$ |

Table III. Numerical results of the strong decay widths for the charmed and bottom baryon sextet with spin 1/2 and 3/2 in MeV. In the second and third columns, those of the charmed baryons and the experimental data are listed respectively, whereas the fifth and last columns represent those of the bottom baryons and corresponding experimental data, respectively.

| decay modes | this work | experiment |
|-------------|-----------|------------|
| $\Sigma_c^+$ | $6.12$ | $9.7^{+4.0}_{-3.0}$ |
| $\Sigma_c^+$ | $6.12$ | $4.9^{+3.3}_{-2.4}$ |
| $\Sigma_c^+$ | $0.7$ | $<0.08$ |
| $\Sigma_c^+$ | $10.96$ | $11.5^{+2.8}_{-2.4}$ |
| $\Sigma_c^+$ | $11.77$ | $7.5^{+2.3}_{-2.4}$ |
| $\Sigma_c^+$ | $0.80$ | $0.9^{+0.18}_{-0.18}$ |
| $\Sigma_c^+$ | $1.28$ | $1.65^{+0.33}_{-0.33}$ |

In Table III, we list the numerical results for the strong decay widths of the charmed baryon sextet in the second column and those of the bottom baryons in the fifth column. The results are in remarkable agreement with the experimental data. It indicates that the pion mean-field approach indeed describes both the light and heavy baryons. Though we have not shown here, the decay widths of the two excited $\Omega_c$’s with smaller decay widths are well reproduced within this framework [12].

5. Conclusion and outlook

In this talk, we presented very concisely a series of the recent works on the properties of the singly heavy baryons, based on the pion mean-field approach or the chiral quark-soliton model. It was shown that the pion mean-field approximation indeed describes both the light and heavy baryons rather well on an equal footing. However, there exists certain points that one needs to go beyond the mean-field approximation. For example, the $1/m_Q$ mass corrections of the heavy quark should be considered in order to describe the properties of the heavy baryons in a quantitative manner, as already seen in the mass spectra. Secondly, if one wants to extend the present scheme to excited baryons, it is inevitable to take into account certain effects of quark confinement at least phenomenologically to keep quarks
inside baryons. The quantum fluctuations or the meson-loop corrections were ignored in the large $N_c$, which leads to the pion mean-field approach. However, the excited baryons require unavoidably the meson-loop effects. Though these extensions and generalization of the mean-field approach are technically complicated, relevant works are under way.

Acknowledgments

I am very grateful to J.-Y. Kim, M. V. Polyakov, M. Praszalowicz, and Gh.-S. Yang for discussion and collaboration. The work is supported by Basic Science Research Program through the National Research Foundation (NRF) of Korea funded by the Korean government (Ministry of Education, Science and Technology(MEST)): Grant No. NRF-2018R1A2B001752 and 2018R1A5A1025563.

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