Magnetic moment of the $\Lambda(1405)$ resonance in the chiral quark model

Neetika Sharma* and Harleen Dahiya
Department of Physics, Dr. B. R. Ambedkar National Institute of Technology, Jalandhar-144011, India.

A. Martínez Torres and K. P. Khemchandani
Instituto de Física, Universidade de São Paulo, C.P 66318, 05314-970 São Paulo, SP, Brazil.

The study of the magnetic moments of the nucleon and its excited spectrum provides valuable insight into the nonperturbative aspects of QCD. Negative parity partners of the baryon octet with $J^P = \frac{1}{2}^-$ arise from excitation of one unit of orbital angular momentum, and their mass splittings can be traced to spontaneous breaking of chiral symmetry of QCD [1]. Although the magnetic moments of the spin $\frac{1}{2}^+$ octet baryons are well-known both experimentally and theoretically, little is known about their spin $\frac{1}{2}^-$ counterparts. Therefore, it would be interesting to examine the QCD predictions for the negative-parity states.

$\Lambda(1405)$ has been attracting much interest from several view points. $\Lambda(1405)$ is the lightest negative-parity baryon in spite of the valence strange quark in it. Among the $J^P = 1/2$ baryons, $\Lambda(1405)$ is much lighter than the non-strange counterpart $N(1535)$, and isolated from the others. Furthermore, the structure of $\Lambda(1405)$ remains mysterious. $\Lambda(1405)$ is interpreted as a flavor-SU(3)-singlet three-quark state in conventional quark models. On the other hand, it can also be interpreted as an antikaon-nucleon $\bar{K}N$ molecular bound state.

In this work, we compute the resonance magnetic moments in the non-relativistic quark model and the chiral constituent quark model. In the $SU(6)$ quark model, the $\Lambda(1405)$ is described as p-wave excitations of the 70-dimensional representation, whose $SU(2) \times SU(3)$ decomposition is given by

$$70 = {}^28 + {}^48 + {}^21 + {}^210 \,. \qquad (1)$$

Here in the notation on the right hand side, ${}^{2j+1}D$, j represents the resonance spin and D the dimension of the flavor $SU(3)$ representation.

Since the Λ particles are isosinglet, their wave functions are spanned by the flavor octet and singlet states. Explicitly, these states are given as [2]

$$\begin{aligned} |{}^28; jm\rangle &= \frac{1}{2}\left([\psi(\rho), \chi_\rho]_{jm}\phi_\lambda + [\psi(\rho), \chi_\lambda]_{jm}\phi_\rho \right. \\ &\quad \left. + [\psi(\lambda), \chi_\rho]_{jm}\phi_\rho - [\psi(\lambda), \chi_\lambda]_{jm}\phi_\lambda\right) , \\ |{}^48; jm\rangle &= \frac{1}{\sqrt{2}}\left([\psi(\lambda), \chi_S]_{jm}\phi_\lambda + [\psi(\rho), \chi_S]_{jm}\phi_\rho\right) , \\ |{}^21; jm\rangle &= \frac{1}{\sqrt{2}}\left([\psi(\rho), \chi_\lambda]_{jm} - [\psi(\lambda), \chi_\rho]_{jm}\right)\phi_a \,. \end{aligned}$$

Here we have employed standard notations.

In the nonrelativistic SU(6) constituent quark model (NCQM), the magnetic moment of the resonances have contribution coming from both quark spin and orbital angular momentum,

$$\boldsymbol{\mu}_B = \boldsymbol{\mu}_B^{\boldsymbol{S}} + \boldsymbol{\mu}_B^{\boldsymbol{L}} \,, \qquad (2)$$

with

$$\boldsymbol{\mu}_B^{\boldsymbol{S}} = \sum_i \boldsymbol{\mu}_i^{\boldsymbol{s}} = \sum_i \frac{Q_i}{2m_i}\, \boldsymbol{s}_i \,, \qquad (3)$$

$$\boldsymbol{\mu}_B^{\boldsymbol{L}} = \sum_i \boldsymbol{\mu}_i^{\boldsymbol{l}} = \sum_i \frac{Q_i}{2m_i}\, \boldsymbol{l}_i \,, \qquad (4)$$

where $\boldsymbol{s_i}$ and $\boldsymbol{l_i}$ are the spin and orbital angular momentum of the ith quark and the index i is sum over three quarks.

*Electronic address: `neetikaphy@gmail.com`

By writing a Λ state as

$$|\Lambda\rangle = a_1|^2 8\rangle + a_2|^4 8\rangle + a_3|^2 1\rangle\,, \quad (5)$$

we find that the various terms can be written as

$$\begin{aligned} \langle^2 8|\mu|^2 8\rangle &= 0\,, \\ \langle^4 8|\mu|^4 8\rangle &= \frac{7}{18}\mu_u + \frac{7}{18}\mu_d + \frac{5}{9}\mu_s\,, \\ \langle^2 1|\mu|^2 1\rangle &= \frac{1}{9}\mu_u + \frac{1}{9}\mu_d + \frac{1}{9}\mu_s\,, \\ \langle^2 8|\mu|^4 8\rangle &= 0\,, \\ \langle^4 8|\mu|^2 1\rangle &= 0\,, \\ \langle^2 8|\mu|^2 1\rangle &= -\frac{1}{9}\mu_u - \frac{1}{9}\mu_d + \frac{2}{9}\mu_s\,. \end{aligned} \quad (6)$$

In the chiral constituent quark model χCQM, the spin contribution μ^S to the magnetic moment of a given baryon receives contributions from the valence quarks, sea quarks, and orbital angular momentum of the "quark sea" [3] and is expressed as

$$\mu_B^S = \mu_{\rm val}^S + \mu_{\rm sea}^S + \mu_{\rm orbit}^S\,, \quad (7)$$

where $\mu_{\rm val}^S$ and $\mu_{\rm sea}^S$ represent the contributions of the valence quarks and the sea quarks to the magnetic moments due to the spin polarizations. The term $\mu_{\rm orbit}^S$ corresponds to the orbital angular momentum contribution of the quark sea.

The orbital angular momentum contribution μ^L to the magnetic moment of a given baryon receives contributions from the valence quark and sea quarks as

$$\mu_B^L = \mu_{\rm val}^L + \mu_{\rm sea}^L\,, \quad (8)$$

where $\mu_{\rm val}^L$ and $\mu_{\rm sea}^L$ represent the contributions of the valence and sea quarks to the magnetic moments due to the orbital angular momentum polarizations.

Using the general formalism, we calculated the magnetic moments of the $\Lambda(1405)$ resonance and the result comes out to be $\mu(\Lambda(1405)) = 0.081$ in χCQM. The results found are comparable with those obtained from the non-relativistic quark model and those of unitary chiral theories.

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