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Heavy quark spin multiplet structure of P_c-like pentaquark as hadronic molecular states

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Exotic hadrons are the very interesting research subjects in hadron and nuclear physics. The X, Y and Z tetraquarks, and the P_c pentaquarks have a heavy quark and an anti-heavy quark. The heavy quark spin (HQS) doublet structure of the single heavy hadron like D and D^* meson is well known. On the other hand, the HQS multiplet structure of the doubly heavy hadron such as $Q\bar{Q}qqq$-type pentaquark has not been researched much. We study the HQS multiplet structure of the $Q\bar{Q}qqq$-type pentaquarks treated as the hadronic molecular state of a heavy meson and a heavy baryon. The light-cloud spin (LCS) basis is defined to study the HQS multiplet of the doubly heavy quark system. Introducing the LCS basis, there exist four- and ten-types of the HQS multiplet classified by the LCS structure for S- and P-wave $\bar{P}^{(*)}\Sigma_Q^{(*)}$ molecular states, respectively.

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1. Introduction

In 2015, the Large Hadron Collider beauty experiment (LHCb) collaboration observed the two hidden-charm pentaquarks, $P_c(4380)$ and $P_c(4450)$[**?**]. Their masses and widths are

$$\begin{aligned} &P_c(4380) \quad M = 4380 \pm 8 \pm 28 \text{ MeV}, \quad \Gamma = 205 \pm 18 \pm 86 \text{ MeV}, \\ &P_c(4450) \quad M = 4449.8 \pm 1.7 \pm 2.5 \text{ MeV}, \quad \Gamma = 39.6 \pm 5 \pm 19 \text{ MeV}. \end{aligned}$$

The spin and parity of them are not well determined. The one state is $J = 3/2$ and the other is $J = 5/2$, and they have opposite parity. After the LHCb observation, many theoretical works in various ways have been conducted and they are summarized in some review papers [**?**, **?**, **?**]. The hadronic molecular picture is one of the highly possible model around the hadron threshold. The threshold of $\bar{D}\Sigma_c^*$ is 4385.3 MeV and $\bar{D}^*\Sigma_c$ is 4462.2 MeV. These values are slightly above the mass of $P_c(4380)$ and $P_c(4450)$, respectively. Therefore, the P_c pentaquarks can be considered as the loosely bound states of a charmed meson and a charmed baryon.

In the heavy quark effective theory, the spin dependent interaction of heavy quark is suppressed by the inverse of the heavy quark mass, $1/m_Q$. At the heavy quark limit, therefore, the dynamics is independent of the transformation of the heavy quark spin. This is called the heavy quark spin symmetry (HQSS). The HQSS leads to the mass degeneracy between the heavy hadrons with different spin. For example, the $J^P = 0^-$ meson P and the 1^- meson P^* degenerate at heavy quark limit. This structure is called the HQS doublet.

The purpose of this work is to study the HQS multiplet structure of $Q\bar{Q}qqq$-type pentaquarks as hadronic molecular states of a $\bar{P}^{(*)}$ meson and a $\Sigma_Q^{(*)}$ baryon. Here $\bar{P}$ and $\bar{P}^*$ denote mesons with $J^P = 0^-$ and 1^- with an anti-heavy quark like $\bar{D}$ and $\bar{D}^*$ mesons, and Σ_Q and Σ_Q^* the baryons with $J^P = 1/2^+$ and $3/2^+$ with a heavy quark like Σ_c and Σ_c^* baryons. The HQS doublet structure of single heavy hadrons such as $\bar{P}^{(*)}$ and $\Sigma_Q^{(*)}$ is well known. On the other hand, the HQS multiplet structure of doubly heavy hadrons like $Q\bar{Q}qqq$ pentaquarks is nontrivial. Hence, it is interesting to investigate the HQS multiplet structure of heavy meson-baryon molecular states.

2. HQS multiplet structure of $\bar{P}^{(*)}\Sigma_Q^{(*)}$

In this section, we consider the HQS multiplet of the $\bar{P}^{(*)}\Sigma_Q^{(*)}$ molecular state. First, we construct the spin structure of the $\bar{P}^{(*)}\Sigma_Q^{(*)}$ in the hadronic molecular (HM) basis. Next, we transfer to the LCS basis by the unitary transformation based on the Refs. [**?**, **?**].

2.1 S-wave molecular state

The possible spins of the $\bar{P}^{(*)}\Sigma_Q^{(*)}$ states with S-wave are

$$\bar{P}\Sigma_Q = \left[S\left[\bar{Q}q\right]_0 [Q[d]_1]_{1/2}\right] = \frac{1}{2}\,, \tag{2.1}$$

$$\bar{P}\Sigma_Q^* = \left[S\left[\bar{Q}q\right]_0 [Q[d]_1]_{3/2}\right] = \frac{3}{2}\,, \tag{2.2}$$

$$\bar{P}^*\Sigma_Q = \left[S\left[\bar{Q}q\right]_1 [Q[d]_1]_{1/2}\right] = \frac{1}{2} \oplus \frac{3}{2}\,, \tag{2.3}$$

$$\bar{P}^*\Sigma_Q^* = \left[S\left[\bar{Q}q\right]_1 [Q[d]_1]_{3/2}\right] = \frac{1}{2} \oplus \frac{3}{2} \oplus \frac{5}{2}\,, \tag{2.4}$$

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where Q, $\bar{Q}$, q and d stand for a heavy quark, anti-heavy quark, light quark and diquark in $\Sigma_Q^{(*)}$ baryon, respectively. The index j of $[\alpha]_j$ means the spin of α. The HM basis is not suitable to discuss the HQS multiplet structure. The heavy quark spin and the light-cloud spin are independently conserved in the heavy quark limit. Thereby, the heavy quark spin and the other spin must be treated separately. The light-cloud spin (LCS) basis is defined as a suitable basis to study the structure of HQS multiplets.

The transformation from the HM basis to the LCS basis is done by the unitary matrices in Ref. [**?**]. The spin structures in LCS basis are given by

$$\left[[\bar{Q}Q]_0\,[q[d]_1]_{1/2}\right] = \frac{1}{2} \quad (\text{singlet}) , \tag{2.5}$$

$$\left[[\bar{Q}Q]_0\,[q[d]_1]_{3/2}\right] = \frac{3}{2} \quad (\text{singlet}) , \tag{2.6}$$

$$\left[[\bar{Q}Q]_1\,[q[d]_1]_{1/2}\right] = \frac{1}{2} \oplus \frac{3}{2} \quad (\text{doublet}) , \tag{2.7}$$

$$\left[[\bar{Q}Q]_1\,[q[d]_1]_{3/2}\right] = \frac{1}{2} \oplus \frac{3}{2} \oplus \frac{5}{2} \quad (\text{triplet}) . \tag{2.8}$$

There are four types of HQS multiplets, $1/2^-$ singlet, $3/2^-$ singlet, $(1/2^-, 3/2^-)$ doublet and $(1/2^-, 3/2^-, 5/2^-)$ triplet. They are classified by the heavy quark spin $S = 0, 1$ and the light cloud spin $j = 1/2, 3/2$.

2.2 P-wave molecular state

The possible spins of the $\bar{P}^{(*)}\Sigma_Q^{(*)}$ states with P-wave are

$$\bar{P}\Sigma_Q\,(^2P) = \left[P\left[[\bar{Q}q]_0\,[Q\,[d]_1]_{1/2}\right]_{1/2}\right] = \frac{1}{2} \oplus \frac{3}{2}, \tag{2.9}$$

$$\bar{P}\Sigma_Q^*\,(^4P) = \left[P\left[[\bar{Q}q]_0\,[Q\,[d]_1]_{3/2}\right]_{3/2}\right] = \frac{1}{2} \oplus \frac{3}{2} \oplus \frac{5}{2}, \tag{2.10}$$

$$\bar{P}^*\Sigma_Q\,(^2P) = \left[P\left[[\bar{Q}q]_1\,[Q\,[d]_1]_{1/2}\right]_{1/2}\right] = \frac{1}{2} \oplus \frac{3}{2}, \tag{2.11}$$

$$\bar{P}^*\Sigma_Q\,(^4P) = \left[P\left[[\bar{Q}q]_1\,[Q\,[d]_1]_{1/2}\right]_{3/2}\right] = \frac{1}{2} \oplus \frac{3}{2} \oplus \frac{5}{2}, \tag{2.12}$$

$$\bar{P}^*\Sigma_Q^*\,(^2P) = \left[P\left[[\bar{Q}q]_1\,[Q\,[d]_1]_{3/2}\right]_{1/2}\right] = \frac{1}{2} \oplus \frac{3}{2}, \tag{2.13}$$

$$\bar{P}^*\Sigma_Q^*\,(^4P) = \left[P\left[[\bar{Q}q]_1\,[Q\,[d]_1]_{3/2}\right]_{3/2}\right] = \frac{1}{2} \oplus \frac{3}{2} \oplus \frac{5}{2}, \tag{2.14}$$

$$\bar{P}^*\Sigma_Q^*\,(^6P) = \left[P\left[[\bar{Q}q]_1\,[Q\,[d]_1]_{3/2}\right]_{5/2}\right] = \frac{3}{2} \oplus \frac{5}{2} \oplus \frac{7}{2} . \tag{2.15}$$

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In the LCS basis, the spin structures are rewritten as follows :

$$\text{(s-1)}: \left[[\bar{Q}Q]_0 \left[P\,[q\,[d]_1]_{1/2}\right]_{1/2}\right] = \frac{1}{2}\,, \tag{2.16}$$

$$\text{(s-2)}: \left[[\bar{Q}Q]_0 \left[P\,[q\,[d]_1]_{3/2}\right]_{1/2}\right] = \frac{1}{2}\,, \tag{2.17}$$

$$\text{(s-3)}: \left[[\bar{Q}Q]_0 \left[P\,[q\,[d]_1]_{1/2}\right]_{3/2}\right] = \frac{3}{2}\,, \tag{2.18}$$

$$\text{(s-4)}: \left[[\bar{Q}Q]_0 \left[P\,[q\,[d]_1]_{3/2}\right]_{3/2}\right] = \frac{3}{2}\,, \tag{2.19}$$

$$\text{(s-5)}: \left[[\bar{Q}Q]_0 \left[P\,[q\,[d]_1]_{3/2}\right]_{5/2}\right] = \frac{5}{2}\,, \tag{2.20}$$

$$\text{(d-1)}: \left[[\bar{Q}Q]_1 \left[P\,[q\,[d]_1]_{1/2}\right]_{1/2}\right] = \frac{1}{2} \oplus \frac{3}{2}\,, \tag{2.21}$$

$$\text{(d-2)}: \left[[\bar{Q}Q]_1 \left[P\,[q\,[d]_1]_{3/2}\right]_{1/2}\right] = \frac{1}{2} \oplus \frac{3}{2}\,, \tag{2.22}$$

$$\text{(t-1)}: \left[[\bar{Q}Q]_1 \left[P\,[q\,[d]_1]_{1/2}\right]_{3/2}\right] = \frac{1}{2} \oplus \frac{3}{2} \oplus \frac{5}{2}\,, \tag{2.23}$$

$$\text{(t-2)}: \left[[\bar{Q}Q]_1 \left[P\,[q\,[d]_1]_{3/2}\right]_{3/2}\right] = \frac{1}{2} \oplus \frac{3}{2} \oplus \frac{5}{2}\,, \tag{2.24}$$

$$\text{(t-3)}: \left[[\bar{Q}Q]_1 \left[P\,[q\,[d]_1]_{3/2}\right]_{5/2}\right] = \frac{3}{2} \oplus \frac{5}{2} \oplus \frac{7}{2}\,. \tag{2.25}$$

There exist five HQS singlets (s-1 to s-5), two HQS doublets (d-1 and d-2), and three HQS triplets (t-1 to t-3). The unitary transformation matrices are shown in Ref. [**?**].

3. One pion exchange potential

In Refs. [**?**, **?**], the one-pion exchange potential (OPEP) is constructed to study that which type of the HQS multiplet have an attractive potential. For the $\bar{P}^{(*)}\Sigma_Q^{(*)}$ coupled channel system, the potential matrices have many off-diagonal components in the HM basis. On the other hand, the potential matrices are diagonalized in the LCS basis.

The behavior of the OPEP is classified by the LCS structure. Heavy quark spin does not effect on the interaction of the one-pion exchange. Here, we focus on the S-wave molecular states. The $3/2^-$ singlet and the $(1/2^-, 3/2^-, 5/2^-)$ triplet have a same attractive potential under the one-pion exchange. Both of them have the same LCS structure, $[q[d]_1]_{3/2}$. On the contrary, the $1/2^-$ singlet and the $(1/2^-, 3/2^-)$ doublet have a repulsive potential and their LCS structure are $[q[d]_1]_{1/2}$. The OPEP depends on only the structure of the LCS.

The P-wave states can be also classified by the LCS structure as discussed in Ref. [**?**]. It can be said that LCS structure have the information of the potential.

4. Summary and discussion

The LCS basis is defined to study the HQS multiplet structure of the $\bar{P}^{(*)}\Sigma_Q^{(*)}$ molecular states. There are four- and ten-types of the HQS multiplet for S- and P-wave state, respectively. Especially, the HQS triplet state does not exist in single heavy hadrons. It is a feature of the multi-heavy quark system.

The potential matrix is block diagonalized in the LCS basis for each HQS multiplet. The behavior of the potential is classified by the structure of the light-cloud spin. As mentioned in Ref. [**?**], OPEP depends only on the structure of the LCS since the pion exchange interaction just couples the light quark spin and the orbital angular momentum. Therefore, the HQS multiplets having the same LCS structure are degenerate at the heavy quark limit. The mass degeneracy is resolved for hidden-charm/bottom pentaquarks because of the finite quark mass.

The spin and parity of P_c are not well determined in the LHCb announcement. The information of them are very important to understand the HQS multiplet structure of hadronic molecular states. We expect to see more details and missing HQS partner states in the future experiments.

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