Physics Letters B 727 (2013) 185–189

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Spin degeneracy in multi-hadron systems with a heavy quark

Shigehiro Yasui [a,*], Kazutaka Sudoh [b], Yasuhiro Yamaguchi [c], Shunsuke Ohkoda [c], Atsushi Hosaka [c], Tetsuo Hyodo [d,1]

[a] KEK Theory Center, Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization, 1-1, Oho, Ibaraki, 305-0801, Japan
[b] Nishogakusha University, 6-16, Sanbancho, Chiyoda, Tokyo, 102-8336, Japan
[c] Research Center for Nuclear Physics (RCNP), Osaka University, Ibaraki, Osaka, 567-0047, Japan
[d] Department of Physics, Tokyo Institute of Technology, Tokyo 152-8551, Japan

ARTICLE INFO

Article history:
Received 18 September 2013
Received in revised form 1 October 2013
Accepted 7 October 2013
Available online 16 October 2013
Editor: B. Grinstein

Keywords:
Heavy quark effective theory
Heavy meson effective theory
Exotic hadrons
Exotic nuclei

ABSTRACT

We study multi-hadron systems with a single heavy quark (charm or bottom) in the limit of heavy quark mass. The spin degeneracy of the states with quantum numbers $(j+1/2)^P$ and $(j-1/2)^P$ for $j \neq 0$, known in a normal hadron, can be generalized to multi-hadron systems. The spin degeneracy is the universal phenomena for any multi-hadron systems with a single heavy quark, irrespective of their internal structures, including compact multi-quarks, hadronic molecules and exotic nuclei. We demonstrate the spin degeneracy in the hadronic systems formed by a heavy hadron effective theory: $P^{(*)}N$ states with a $P^{(*)} = \bar{D}^{(*)}$, $B^{(*)}$ meson and a nucleon N, and a $P^{(*)}$ meson in nuclear matter. The spin degeneracy in the multi-hadron systems with a single heavy quark provides us with useful information about mass spectra, decays and productions in a model-independent manner.

Recent experimental developments in hadron spectroscopy have unveiled the existence of various exotic hadrons which are considered to have extraordinary structures. To analyze their properties is intimately related to the fundamental problems in QCD, such as color confinement and dynamical chiral symmetry breaking. Especially for charm and bottom flavors, there have been many experimental evidences for the existence of the exotic hadrons, such as X, Y and Z for charm sector and Y_b and Z_b for bottom sector [1]. Theoretically, not only exotic hadrons, but also exotic nuclei with charm and bottom are discussed. Those states can be explored experimentally at facilities, such as J-PARC, GSI-FAIR, RHIC and LHC [2]. Heavy exotic hadrons and nuclei will bring us a new insight from the quark dynamics to the nuclear dynamics, which cannot be accessed by light flavor hadrons. Although many model calculations have been extensively performed in the literature, it will be eagerly required to have the rigorous knowledge directly based on QCD.

A unique feature of charm and bottom quarks is that their masses are heavier than the energy scale of light quark QCD. In the heavy mass limit, it leads to the spin symmetry [3–7]. It has been known that, in a hadron with a single heavy quark, the spin of the heavy quark is decoupled from the total angular momentum of the light quarks and gluons, the "brown muck" which is everything other than the heavy quark in the hadron [8]. As a consequence, there appears a pair of degenerate states with total angular momentum and parity, $(j-1/2)^P$ and $(j+1/2)^P$, for $j \neq 0$, while a single state for $j = 0$, where j is the total angular momentum of the brown muck. The spin degeneracy has been addressed in the context of normal hadrons, such as mesons and baryons including excited states [4–11].

The purpose of the present Letter is to apply the idea of the spin degeneracy to multi-hadron systems such as exotic hadrons (irrespective of multi-quarks, hadronic molecules and exotic nuclei) containing a single heavy quark. We investigate the spin degeneracy in the hadronic effective theory of QCD, where the fundamental degrees of freedom are given by hadrons, and show that hadronic molecules with baryon number one and heavy mesons in nuclear matter exhibit the spin degeneracy. Throughout the discussion, we assume non-negative baryon numbers for the multi-hadron systems. The cases of negative baryon numbers will be immediately obtained.

First of all, let us consider the spin degeneracy in multi-hadron systems in views of QCD. This is a general discussion so that the conclusion should hold in any multi-hadron systems, as far as the heavy quark limit is adopted. Denoting the four velocity of the heavy quark as v^μ with $v^2 = 1$, we introduce the effective field $Q_v(x) = e^{im_Q v\cdot x}\frac{1+\not{v}}{2}Q(x)$ for projecting out the positive

* Corresponding author.
E-mail address: yasuis@post.kek.jp (S. Yasui).
[1] Present address: Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto, 606-8317, Japan.

0370-2693/$ – see front matter
http://dx.doi.org/10.1016/j.physletb.2013.10.019

energy component of the heavy quark field $Q(x)$. The effective Lagrangian in the $1/m_{\rm Q}$ expansion is given by

$$\mathcal{L}_{\rm HQET} = \bar{Q}_v v \cdot iD Q_v + \mathcal{O}(1/m_{\rm Q}), \tag{1}$$

with the covariant derivative D_μ. This is the Lagrangian with a leading term in the heavy quark effective theory (HQET) [3–7]. A hadron with a single heavy quark is composed of the heavy quark with spin $\boldsymbol{S}$ and the brown muck with total angular momentum $\boldsymbol{j}$. The total angular momentum of the hadron is $\boldsymbol{J} = \boldsymbol{S} + \boldsymbol{j}$. In the limit of heavy quark mass ($m_{\rm Q} \to \infty$), $\boldsymbol{S}$ is a conserved quantity, because the spin flip terms are absent in the leading order in the $1/m_{\rm Q}$ expansion of $\mathcal{L}_{\rm HQET}$. This is called the heavy quark spin (HQS) symmetry. Clearly $\boldsymbol{J}$ is conserved. Therefore, we find that $\boldsymbol{j}$ is conserved, even though the brown muck is a highly non-perturbative object. Thus, we confirm that the spin degeneracy is realized as addressed previously.

Interestingly, the notion of the spin degeneracy is generally applied, not only to normal hadrons in ground states and higher exited states, but also to multi-hadron systems and even to exotic nuclear systems, as far as the states contain a single heavy (anti)quark. Here we consider exotic hadrons with a single heavy antiquark, whose quark contents are minimally given by $\bar{Q}q^n$ ($n = 3B + 1$ with baryon number $B \geqslant 0$) with a heavy antiquark $\bar{Q}$ and many light quarks q. We should note that the state is in fact a superposition of n light quarks plus any number of $q\bar{q}$ pairs and gluons g for a given quantum number;

$$\bar{Q}\,\underbrace{q\cdots q}_{n} + \bar{Q}\,\underbrace{q\cdots q}_{n} q\bar{q} + \bar{Q}\,\underbrace{q\cdots q}_{n} q\bar{q}g + \cdots. \tag{2}$$

Then, we ask the question whether the exotic hadrons have the spin degeneracy as normal hadrons. In those systems, the heavy quark spin for $\bar{Q}$ is a conserved quantity in the heavy mass limit, and the total angular momentum is also conserved. Therefore, the total angular momentum of the ensemble of the light components, $q\cdots q + q\cdots qq\bar{q} + q\cdots qq\bar{q}g + \cdots$, in Eq. (2) is also conserved. Consequently, we obtain the result that there is a pair of degenerate states with $(j-1/2)^P$ and $(j+1/2)^P$ for $j \neq 0$, and a single state for $j = 0$, where $j^{\mathcal{P}}$ is the total angular momentum and parity of the light components ($\mathcal{P} = -P$). Hereafter we call those states “HQS doublets” for $j \neq 0$ and “HQS singlets” for $j = 0$, respectively.

In the present discussion, we call the light components in Eq. (2) “light spin-complex” (or “spin-complex” in short). The reason for introducing the new term is explained. When the state is a compact multi-quark, the spin-complex is an ensemble of light quarks and gluons. This is the ordinary situation for the brown muck in a normal hadron. When the state is a *spatially extended hadronic molecule*, however, the state can be composed of light hadrons and the $\bar{Q}q$ meson. Then, the spin-complex is a composite system with light hadrons and light components in the $\bar{Q}q$ meson. Here we use “spin” to emphasize the importance of spin degrees of freedom. As a typical configuration, it can be $q\bar{q}$ mesons and a light quark q for $B = 0$, or qqq baryons and a light quark q for $B \geqslant 1$. The latter can be applied to the exotic nuclei containing the $\bar{Q}q$ meson, as discussed later. We discriminate the spin-complex from the conventional brown muck, in the sense that the spin-complex describes the composite systems by quarks, gluons and hadrons.

How the spin-complex is formed is a highly non-perturbative problem in QCD. However, the spin-complex is a useful object to classify exotic hadrons, when it carries a good quantum number $j^{\mathcal{P}}$. Therefore, the spin (non-)degeneracy for $j \neq 0$ ($j = 0$) is a universal phenomena regardless whether the state is a compact multi-quark state, an extended hadronic molecule state or even a mixture of them.

From the above discussions, the spin degeneracy can occur in any multi-hadron systems with a single heavy quark, such as hadronic molecules and nuclei, in the heavy quark limit. However, it is not known a priori how the spin degeneracy occurs in the *heavy hadron effective theory*. Specifically, it is not a trivial problem whether the ground state is a HQS doublet or a HQS singlet. This is the main subject which will be investigated as follows.

To start with, let us discuss hadronic molecules with genuinely exotic quark content $\bar{Q}qqqq$. We assume that they are compound by a heavy meson $P^{(*)} \sim \bar{Q}q$ and a nucleon N. We denote the heavy meson with $J^P = 0^-$ (1^-) as P (P^*), and $P^{(*)}$ stands for one of the HQS doublet (P, P^*). We study whether the $P^{(*)}N$ systems exhibit the spin degeneracy in terms of the heavy meson effective theory.

To demonstrate concretely, we consider the one pion exchange potential between $P^{(*)}$ and N in Refs. [12,13]. The heavy quark symmetry is realized in the degenerate masses of P and P^* and the common couplings of πPP^* and πP^*P^* vertices. We will investigate the states with $1/2^-$ and $3/2^-$ in detail, and later will extend the discussion to general cases of $(j-1/2)^P$ and $(j+1/2)^P$.

The wave function in $P^{(*)}N$ has multi-channels;

$$\bigl\{\bigl|PN\bigl({}^2\mathrm{S}_{1/2}\bigr)\bigr\rangle, \bigl|P^*N\bigl({}^2\mathrm{S}_{1/2}\bigr)\bigr\rangle, \bigl|P^*N\bigl({}^4\mathrm{D}_{1/2}\bigr)\bigr\rangle\bigr\}, \tag{3}$$

for $1/2^-$ and

$$\bigl\{\bigl|PN\bigl({}^2\mathrm{D}_{3/2}\bigr)\bigr\rangle, \bigl|P^*N\bigl({}^4\mathrm{S}_{3/2}\bigr)\bigr\rangle, \bigl|P^*N\bigl({}^4\mathrm{D}_{3/2}\bigr)\bigr\rangle, \bigl|P^*N\bigl({}^2\mathrm{D}_{3/2}\bigr)\bigr\rangle\bigr\}, \tag{4}$$

for $3/2^-$. Then, the Hamiltonians are given by

$$H_{1/2^-} = \begin{pmatrix} K_0 & \sqrt{3}C & -\sqrt{6}T \\ \sqrt{3}C & K_0 - 2C & -\sqrt{2}T \\ -\sqrt{6}T & -\sqrt{2}T & K_2 + (C - 2T) \end{pmatrix}, \tag{5}$$

$$H_{3/2^-} = \begin{pmatrix} K_2 & \sqrt{3}T & -\sqrt{3}T & \sqrt{3}C \\ \sqrt{3}T & K_0 + C & 2T & T \\ -\sqrt{3}T & 2T & K_2 + C & -T \\ \sqrt{3}C & T & -T & K_2 - 2C \end{pmatrix}, \tag{6}$$

for $1/2^-$ and $3/2^-$, respectively. We define the kinetic term $K_\ell = -(\partial^2/\partial r^2 + (2/r)\partial/\partial r - \ell(\ell+1)/r^2)/2\mu$ for angular momentum ℓ, and the reduced mass μ coincides with the mass of the nucleon m_N in the limit of infinite mass of $P^{(*)}$. We also define $C = \kappa\, C(r; m_\pi)$ and $T = \kappa\, T(r; m_\pi)$, with $\kappa = (g_\pi g_{\pi NN}/\sqrt{2}m_N f_\pi)(\boldsymbol{\tau}_P \cdot \boldsymbol{\tau}_N/3)$ with a $P^{(*)}P^*\pi$ $(NN\pi)$ coupling constant g_π $(g_{\pi NN})$, the pion decay constant f_π, and isospin matrices $\boldsymbol{\tau}_P$ and $\boldsymbol{\tau}_N$ for $P^{(*)}$ and N, respectively, and the central potential $C(r; m_\pi)$ and the tensor potential $T(r; m_\pi)$ (r the distance between $P^{(*)}$ and N, and m_π the pion mass) whose explicit forms are given in Refs. [12,13]. The PN and P^*N states can be mixed, and the states with different angular momenta can also be mixed. The former originates in the heavy quark spin symmetry, and the latter does in the tensor force of the pion exchange potential.

Previously we mentioned the existence of the spin-complex in the multi-hadron systems. We then ask what the spin-complex in the present $P^{(*)}N$ system is. We remember that the $P^{(*)}N$ molecule state is composed of the meson $P^{(*)} \sim \bar{Q}q$ and a nucleon N. In view of the heavy quark spin symmetry, this system is decomposed into the heavy antiquark $\bar{Q}$ and the remaining light degrees of freedom, namely the spin-complex. In our model space, the spin-complex is given by Nq from the nucleon N and the light quark q in $P^{(*)}$. Combined with the heavy antiquark $\bar{Q}$, the basis states can be written as

$$\bigl\{\bigl|[Nq]^{(0,\mathrm{S})}_{0^+}\,\bar{Q}\bigr\rangle_{1/2^-}, \bigl|[Nq]^{(1,\mathrm{S})}_{1^+}\,\bar{Q}\bigr\rangle_{1/2^-}, \bigl|[Nq]^{(1,\mathrm{D})}_{1^+}\,\bar{Q}\bigr\rangle_{1/2^-}\bigr\}, \tag{7}$$

and