Non-perturbative HQET parameters for singly heavy baryons

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Introduction

The singly heavy baryons are observed recently by many collaborations. The baryons are studied using many theoretical models. In 2020, LHCb collaboration [1] observed a new baryon state in the $\Lambda_b^0\pi^+\pi^-$ mass spectrum with mass $m_{\Lambda_b^{**0}} = 6072.3 \pm 2.9 \pm 0.6 \pm 0.2$ MeV and natural width $\Gamma = 72 \pm 11 \pm 2$ MeV. In 2017, LHCb [2] observed five new narrow excited Ω_c^0 states in the $\Xi_c^+K^-$ mass spectrum with the sample of pp collision data corresponding to an integrated luminosity of 3.3 fb^{-1}, collected by the LHCb experiment. The heavy quark effective theory (HQET) is a useful tool to exploit the symmetries of heavy-light systems. The leading order non-perturbative parameters of HQET upto $\frac{1}{m_Q}$ are $\overline{\Lambda}$, λ_1 and λ_2^Q. In limit $m_Q \to \infty$, the $\frac{1}{m_Q}$ term in HQET Lagrangian vanishes. The higher order parameters λ_1 and λ_2 have a smaller contribution in mass. The lattice QCD [3] was employed to compute the non-perturbative parameters, $\overline{\Lambda} = 0.68^{+0.02}_{-0.12}$ GeV and $\lambda_1 = -(0.45 \pm 0.12)$ GeV^2. Using sum rules within the framework of HQET in Ref. [4], parameters $\overline{\Lambda}_\Lambda = 0.79 \pm 0.05$ GeV for Λ_Q baryons and $\overline{\Lambda}_\Sigma = 0.96 \pm 0.05$ for $\Sigma_Q^{(*)}$ baryons were calculated. Also, they computed heavy quark masses to be $m_c = 1.43 \pm 0.05$ GeV and $m_b = 4.83 \pm 0.07$ GeV. The non-perturbative parameters of HQET are calculated for ground state singly heavy charm and bottom baryons.

1. Framework

The HQET Lagrangian comes from QCD Lagrangian by expanding QCD Lagrangian in terms of $\frac{1}{m_Q}$. The heavy quarks symmetry breaking effects comes from the higher terms of HQET Lagrangian which depends on the heavy quark mass (m_Q). In the limit $m_Q \to \infty$, the heavy quark velocity is the velocity of hadron. The HQET Lagrangian is given as

$$\mathcal{L} = \overline{Q}_v(iv.D)Q_v - \overline{Q}_v\frac{D_\perp^2}{2m_Q}Q_v - a(\mu)g\overline{Q}_v\frac{\sigma_{\mu\nu}G^{\mu\nu}}{4m_Q}Q_v \quad (1)$$

where, $D_\perp \equiv D^\mu - D.vv^\mu$ and $D^\mu \equiv \partial^\mu - igA^\mu$ is the covariant derivative. v is the heavy quark velocity. Q_v is effective heavy field. $G^{\mu\nu}$ is the gluon field strength tensor. Only the first term survives in the limit $m_Q \to \infty$. Higher terms contain $\frac{1}{m_Q}$ factor and thus breaks the heavy quark symmetry. All hadrons containing a single heavy heavy quark (Q) are degenerate at order m_Q, and have same mass m_Q. At order m_Q^0, the hadron masses gets a contribution from the first term of the Lagrangian as shown in Eq. (1). The first contribution in mass is $\overline{\Lambda} \equiv \frac{1}{2}\left\langle H^{(Q)}|H_0|H^{(Q)}\right\rangle$. H_0 is the $\frac{1}{m_Q^0}$ order term of the Hamiltonian of HQET obtained from the first term of Lagrangian. It has the same value for all particles in a spin-flavor multiplet. The higher order corrections obtained in similar manner are λ_1 and λ_2^Q. The λ_1 HQET parameter independent of m_Q but λ_2^Q depends on m_Q. The masses of S-wave baryons containing single charm and bottom quarks are given in as.

$$m_{\Lambda_Q} = m_Q + \overline{\Lambda}_\Lambda - \frac{\lambda_{\Lambda,1}}{2m_Q} \quad (2a)$$

$$m_{\Sigma_Q} = m_Q + \overline{\Lambda}_\Sigma - \frac{\lambda_{\Sigma,1}}{2m_Q} - \frac{2\lambda_{\Sigma,2}^c}{m_Q} \quad (2b)$$

$$m_{\Sigma_Q^*} = m_Q + \overline{\Lambda}_\Sigma - \frac{\lambda_{\Sigma,1}}{2m_Q} + \frac{\lambda_{\Sigma,2}^c}{m_Q} \quad (2c)$$

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The coefficients of λ_2 are represented by the spin orbit interaction of heavy and light quarks and distinguishes the spin partners ($\Sigma(\frac{1}{2}^+)$ and $\Sigma^*(\frac{3}{2}^+)$).

2. Result and Discussion

The non-perturbative parameters ($\overline{\Lambda}$, λ_1, λ_2) of HQET are useful to find masses, form factors, decay width, etc [5]. The masses of heavy-light hadrons are very much dependent on the nature of these non-perturbative parameters. These parameters are well studied for heavy-light mesons. We have computed the HQET parameters with $m_c = 1290$ MeV and $m_b = 4670$ MeV different from the masses given in PDG [6]. By changing the heavy quark masses, we can understand the behaviour of heavy quark inside hadrons. The parameters and contribution of mass terms change significantly with the heavy quark masses. The masses and charm and bottom baryons are given table I. The values given in Table II of parameters are calculated from the available masses of singly heavy charm and bottom baryons. The $\overline{\Lambda}$ parameter is same for particles in the same multiplet. As Σ_Q, Ξ'_Q, and Ω_Q lie in the same multiplet, the $\overline{\Lambda}$ should have been same for all. The difference comes from the inclusion of strange quark. As light quarks (u, d, s) form an approximate SU(3) symmetry and it breakdown due the mass of s quark. From table II, we can see that the $\overline{\Lambda}_\Sigma - \overline{\Lambda}_{\Xi'} \sim \overline{\Lambda}_{\Xi'} - \overline{\Lambda}_\Omega \sim 120$ MeV. This symmetry of parameters is a key feature of HQET.

J^P	Baryons	$Q = c$	$Q = b$
$\frac{1}{2}^+$	Λ	2286.46 ± 0.14	5619.60 ± 0.17
	Ξ	2469.08 ± 0.18	5794.45 ± 0.40
	Σ	2453.54 ± 0.15	5813.10 ± 0.18
	$\Xi^{'}$	2578.45 ± 0.35	5935.02 ± 0.05
	Ω	2695.2 ± 1.7	6046.1 ± 1.7
$\frac{3}{2}^+$	Σ^*	2518.13 ± 0.8	5832.53 ± 0.20
	$\Xi^{'*}$	2645.63 ± 0.20	5953.82 ± 0.31
	Ω^*	2766.0 ± 2.0	6082 ± 20*

TABLE I: The masses of S-wave charm and bottom baryons are shown in MeV. The mass of Ω_b^* is taken from Ref. [7] and all other masses are taken from PDG.

$\overline{\Lambda}_\Lambda$	$\lambda_{\Lambda,1}$	$\overline{\Lambda}_\Xi$	$\lambda_{\Xi,1}$
931	-0.17×10^6	1103	-0.19×10^6
$\overline{\Lambda}_\Sigma$	$\lambda_{\Sigma,1}$	$\lambda^c_{\Sigma,2}$	$\lambda^b_{\Sigma,2}$
1136	-0.18×10^6	2.78×10^4	3.02×10^4
$\overline{\Lambda}_{\Xi'}$	$\lambda_{\Xi',1}$	$\lambda^c_{\Xi',2}$	$\lambda^b_{\Xi',2}$
1256	-0.20×10^6	2.89×10^4	2.93×10^4
$\overline{\Lambda}_\Omega$	$\lambda_{\Omega,1}$	$\lambda^c_{\Omega,2}$	$\lambda^b_{\Omega,2}$
1380	-0.19 x 10^6	3.04×10^4	5.59×10^4

TABLE II: Computed parameters for $n = 1$ S-wave baryons. The parameters $\overline{\Lambda}$ are in units MeV. λ_1 and λ_2 are in MeV^2 units.

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