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Regge-like relation and a universal description of heavy-light systems*

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Using the Regge-like formula $(M-m_Q)^2=\pi\sigma L$ between hadron mass M and angular momentum L with a heavy quark mass m_Q and a string tension σ, we analyze all the heavy-light systems, i.e., $D/D_s/B/B_s$ mesons and charmed and bottom baryons. Numerical plots are obtained for all the heavy-light mesons of experimental data whose slope becomes nearly equal to 1/2 of that for light hadrons. Assuming that charmed and bottom baryons consist of one heavy quark and one light cluster of two light quarks (diquark), we apply the formula to all the heavy-light baryons including recently discovered Ω_c's and find that these baryons experimentally measured satisfy the above formula. We predict the average mass values of B, B_s, Λ_b, Σ_c, Ξ_c, and Ω_c with $L=2$ as 6.01, 6.13, 6.15, 3.05, 3.07, and 3.34 GeV, respectively. Our results on baryons suggest that these baryons can be safely regarded as heavy quark-light cluster configuration. We also find a universal description for all the heavy-light mesons as well as baryons, i.e., one unique line is enough to describe both of charmed and bottom heavy-light systems. Our results suggest that instead of mass itself, gluon flux energy is essential to obtain a linear trajectory.

XVII International Conference on Hadron Spectroscopy and Structure - Hadron2017
25-29 September, 2017
University of Salamanca, Salamanca, Spain

*This talk is based on arXiv:1709.07196.
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PoS(Hadron2017)071

1. Numerical plots for heavy-light systems and universal description

Based on the idea of Ref. [1], we can derive the following equation for heavy-light systems,

$$(M - m_Q)^2 = \pi\sigma L, \quad m_c = 1.55 \text{ GeV}, \quad m_b = 4.88 \text{ GeV}, \tag{1.1}$$

where we adopt the heavy quark masses used in Refs. [2, 3]. This is because all the figures for experimental data are compared with model calculations given by Ref. [2, 3].

We would like to show how effective the equation (1.1) is for heavy-light systems and claim that heavy-light baryons can be safely regarded as heavy quark-diquark systems. According to Eq. (1.1), we plot figures for heavy-light mesons, $D/B/D_s/B_s$, as well as charmed and bottom baryons, $\Lambda_Q/\Sigma_Q/\Xi_Q/\Xi'_Q/\Omega_Q$ with $Q = c, b$, for experimental data listed in PDG [4] and some theoretical models Refs. [2, 3, 5].

1.1 Heavy-Light Mesons

In this subsection, we plot figures in $(M - m_Q)^2$ versus L for D, B, D_s, and B_s mesons taken from experimental data [4] as well as model calculations of Ref. [2].

D/B mesons : Using data of PDG [4], the results are given in the upper-left of Figs. 1 for D and B mesons together. To compare Eq. (1.1) with that of Ref. [6], we give a numerical value of the coefficient of L obtained by Afonin,

$$M^2 = 1.103L + 1.102n + 0.686. \tag{1.2}$$

which is taken from Table 4 of Ref. [6] with principal quantum number n. The calculations of the EFG model [2] for D and B mesons are given by the upper-right of Fig. 1. Looking at linear equations written on Fig. 1, we obtain

$$(M_D - m_c)^2 = 0.665L + 0.130, \tag{1.3}$$
$$(M_B - m_b)^2 = 0.548L + 0.179. \tag{1.4}$$

As one can see, coefficients of L are nearly equal to 1/2 of that of light hadrons in Eq. (1.2). Hence we can conclude that D and B mesons satisfy Eq. (1.1), support an approximate rotational symmetry of heavy-light mesons claimed in the previous paper [7], and the string picture for heavy-light mesons well works. Two lines in the upper-left of Fig. 1 nicely show a universal description of these mesons. This means that two lines almost overlap with each other irrespective of heavy quark flavors. In the same way, we draw a figure for the EFG model [2] which is also given in the upper-right of Fig. 1. We plot two lines for heavy-light systems X_c and X_b in one figure, which makes easy to compare both lines with each other and we can extract conclusions on whether their slopes are close to 1/2 and whether they overlap to confirm a universal description. Finally, we predict the average mass of B with $L = 2$ as 6.01 GeV using Eq. (1.4).

D_s/B_s mesons : In the lower row of Fig. 1, we plot mass squared versus L for D_s/B_s mesons using data of PDG [4], which presents a behavior similar to that for D/B mesons and it is clear that they also satisfy Eq. (1.1). Furthermore, since the values of slope for D_s and B_s are close to each other, D_s and B_s satisfy a universal description. To show a figure for model calculations of D_s/B_s mesons, we plot the figure for these mesons of the EFG model in the lower-right of Fig. 1. This

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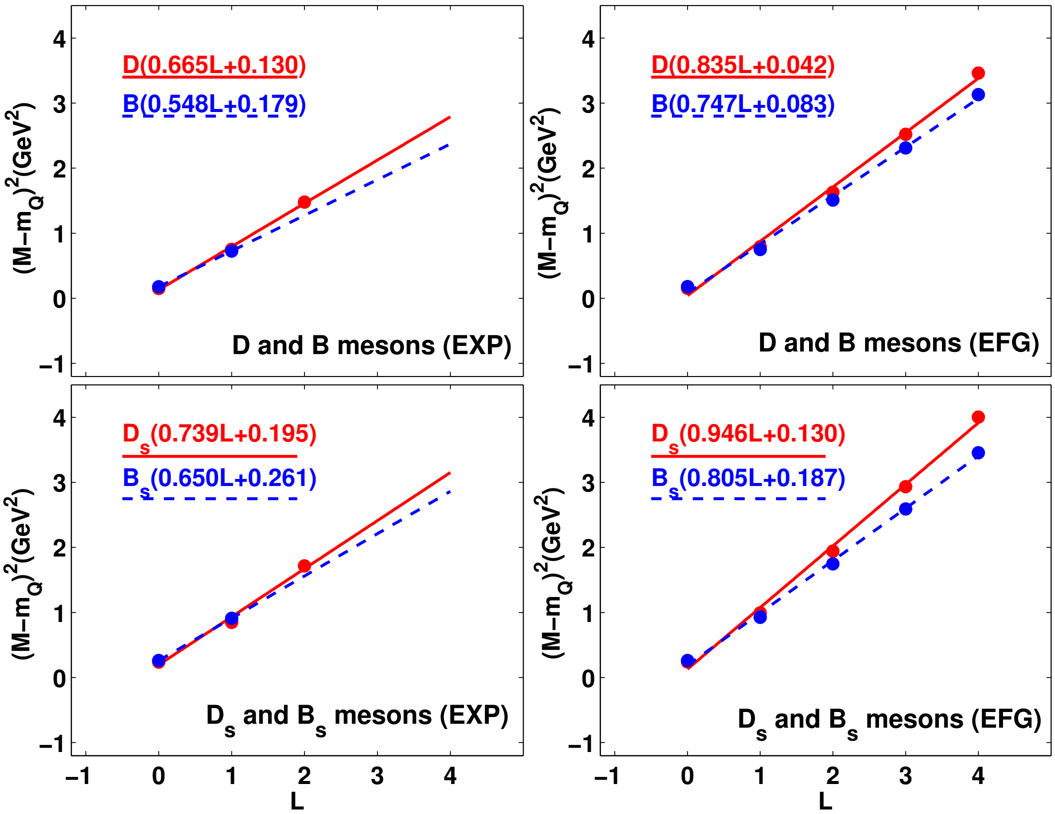

Figure 1: (color online). Plots of experimental data and EFG model [2] calculation both for $D_{(s)}$ and $B_{(s)}$ mesons. The best fit lines are given with equations.

figure shows this model well satisfies a linear equation Eq. (1.1) and two lines almost overlap, i.e., a universal description is confirmed. As one can see, the experimental data behaves much better than the model calculation in regard to a universal description, which may be due to the fact that the EFG model does not explicitly respect heavy quark symmetry. We also predict the average mass of B_s with $L=2$ as 6.13 GeV using $(M_{B_s}-m_b)^2 = 0.650L+0.261$ written on the lower-left of Fig. 1.

1.2 Charmed and Bottom Baryons

Regarding two light quarks inside a heavy-baryon as a light cluster (diquark), we can apply the formula Eq. (1.1) to charmed and bottom baryons, in which only one of c or b quark is included. For the baryons, we take models of Refs. [3, 5] to compare with experiments [4], which include the effect of heavy quark symmetry. We also have to take care of a total spin of a diquark, S_{qq}. We call this system a *good type* when $S_{qq}=0$, and a *bad type* when $S_{qq}=1$ according to Ref. [8].

Λ_c/Λ_b baryons ($I=0$, $S_{qq}=0$) : Λ_Q baryons have $S_{qq}=0$, i.e., a good type. Charmed and bottom Λ_Q baryons have isospin $I=0$ and $S_{qq}=0$. We use the present experimental data of PDG [4] and EFG model results for Λ_Q baryons. Their Regge-like lines are given by the upper row of Fig. 2 for experimental and theoretical values. We take theoretical values from Ref. [3]. From these figures, we can conclude that Eq. (1.1) is satisfied, the slopes are close to 1/2, and hence a unified description holds. We can predict the average mass values of some states which are not yet observed. For instance, by using the line for Λ_b, we predict the average mass of $\Lambda_b(3/2^+,5/2^+)$ with $L=2$ as 6.15 GeV.

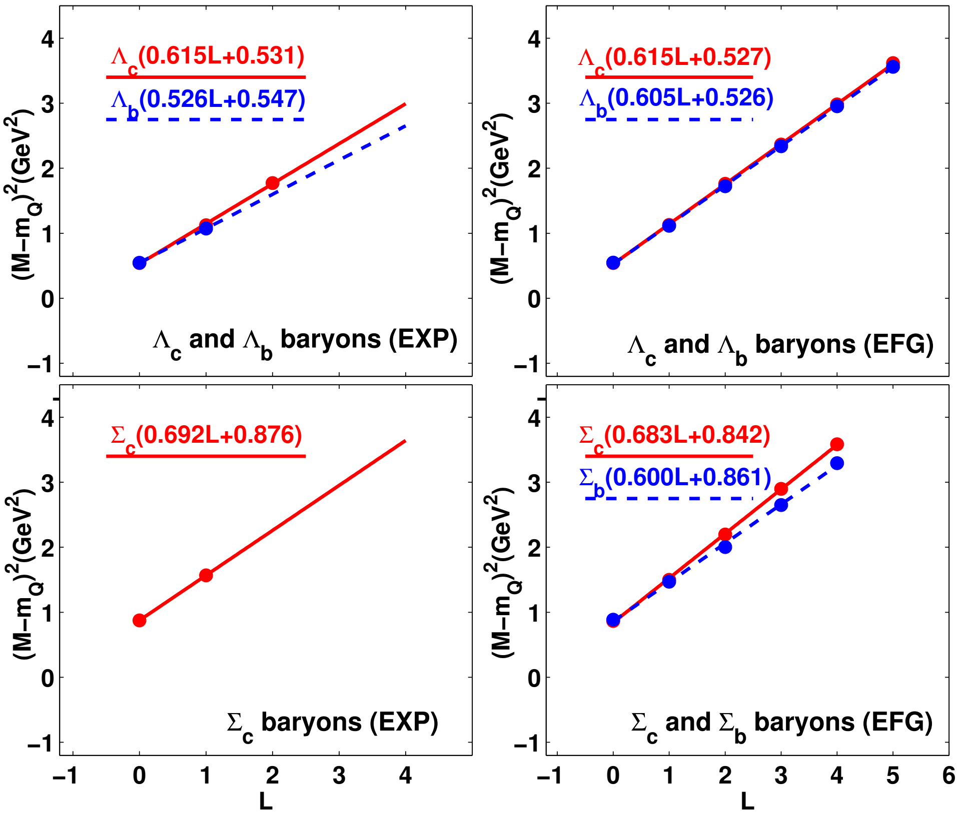

Figure 2: (color online). Plots of experimental data and model calculation [3] for Λ_Q and Σ_Q baryons. The best fit lines are given with equations.

Σ_c/Σ_b baryons $(I=1,\ S_{qq}=1)$: Σ_Q baryons have $S_{qq}=1$, i.e., a bad type. We use the experimental data [4] and EFG model results [3] for Σ_Q baryons. From these values, we can see that only two experimental data for Σ_b with $L=0$ were observed, i.e., only one point in the L vs. $(M-m_b)^2$ plane, and experimental data for Σ_c with $L=0,1$ have been measured. Hence, we can plot figures only for Σ_c of experimental and $\Sigma_{c,b}$ of theoretical values [3] in the lower row of Fig. 2. From these figures, we can conclude again that Eq. (1.1) is satisfied for Σ_c, the slope is close to 1/2, a unified description holds, and the model calculations obey the same behaviors as experimental data, too. We predict the average mass of Σ_c with $L=2$ as 3.05 GeV using the linear equation for Σ_c written on the lower left of Fig. 2.

Ξ_c/Ξ_b baryons $(I=1/2,\ S_{qq}=0)$: Ξ_Q baryons have $S_{qq}=0$, i.e., a good type. The experimental data and theoretical values for Ξ_Q baryons are taken from Refs. [4, 3]. Because of lack of enough experimental data, we can only plot a figure for experimental values of Ξ_c with $L=0,1,2$. Theoretical values of Ref. [3] are taken. Their figures are given by the left two of Fig. 3, respectively. From these figures, we can conclude again that Eq. (1.1) is satisfied for Ξ_c and the slope is close to 1/2. The model calculations obey the same rules as experimental data, too, including a unified description. We predict the average mass of Ξ_c with $L = 2$ as 3.07 GeV using the linear equation for Ξ_c written on the leftmost of Fig. 3.

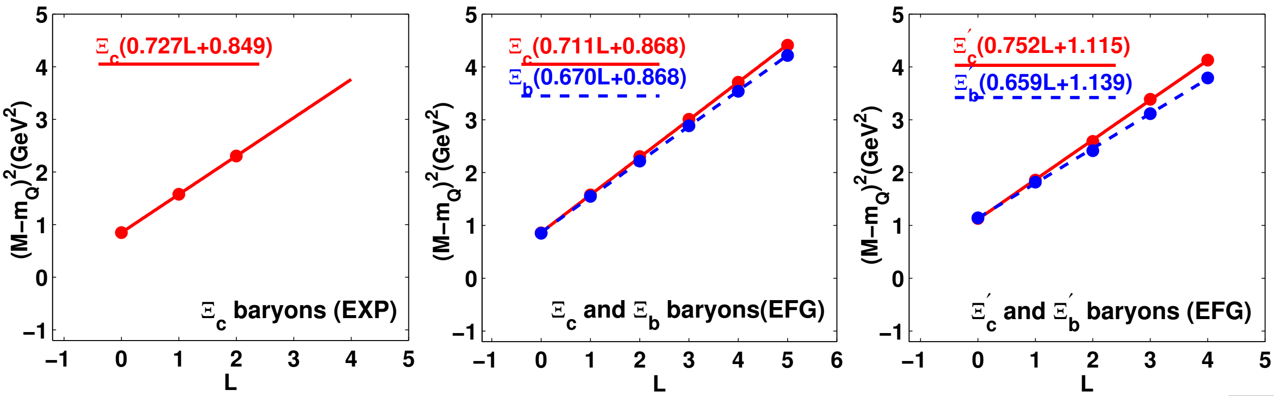

Figure 3: (color online). Plots of experimental data for Ξ_c baryons and model calculation results [3] of Ξ_Q and Ξ'_Q baryons. The best fit lines are given with equations.

Ξ'_c/Ξ'_b baryons ($I = 1/2$, $S_{qq} = 1$) : Ξ'_Q baryons have $S_{qq} = 1$, i.e., a bad type. We also adopt the experimental data and model calculation for Ξ'_Q baryons of Refs. [4, 3], respectively. There is no definite experimental data for Ξ'_Q with $Q = c, b$, and hence, we can only plot figures for Ξ'_Q of model calculations given by Ref. [3]. The figure is given in the rightmost one of Fig. 3, which shows that Eq. (1.1) is satisfied, the slope is close to 1/2, and a unified description holds for theoretical data.

Ω_c/Ω_b baryons ($I = 1$, $S_{qq} = 1$) : Ω_Q baryons have $S_{qq} = 1$, i.e., a bad type. Recently the LHCb Collaboration has observed six Ω_c^0 in the $\Xi_c^+ K^-$ invariant mass spectrum [9]. However, there is only one Ω_b state with $L = 0$ listed in [4], and hence we cannot draw a figure. We also plot the left of Fig. 4 for Ω_c of experimental data and the right of Fig. 4 for Ω_c and Ω_b of the theoretical calculation in Ref. [3]. Besides, since there might be higher radial excited states in the recent discovery by LHCb, we also plot figures with principal quantum number $n = 1, 2$ for theoretical values [3, 5] in Ref. [10]. We predict the average mass of Ω_c with $L = 2$ as 3.34 GeV using the linear equation for Ω_c written on the left of Fig. 4.

Since lack of experimental data for Ω_Q, the slope is not reliable enough to determine which model is most preferable. Reference [3] satisfies Eq. (1.1) (EFG), the slope is close to 1/2 and a universal description holds for theoretical data. As for two values of n, there are two figures obtained by the same group, whose figures are slightly different from each other. The second has larger slope than the first one and hence, it can be rejected from our point of view. The other two diagrams plotted with the results from CL [5] and EFG [3] models are similar to the plot obtained from another group and it may be possible that these three could be close to experiments, which we expect to have in future.

In this paper [10], we have checked whether Eq. (1.1) holds for all the heavy-light systems of mesons and baryons or not and we have confirmed that they do satisfy this equation and a universal description also holds for these hadrons. Equation (1.1) means, in a sense, the relation between flux energy of a heavy-light system and an angular momentum. That is, for heavy-light systems, we

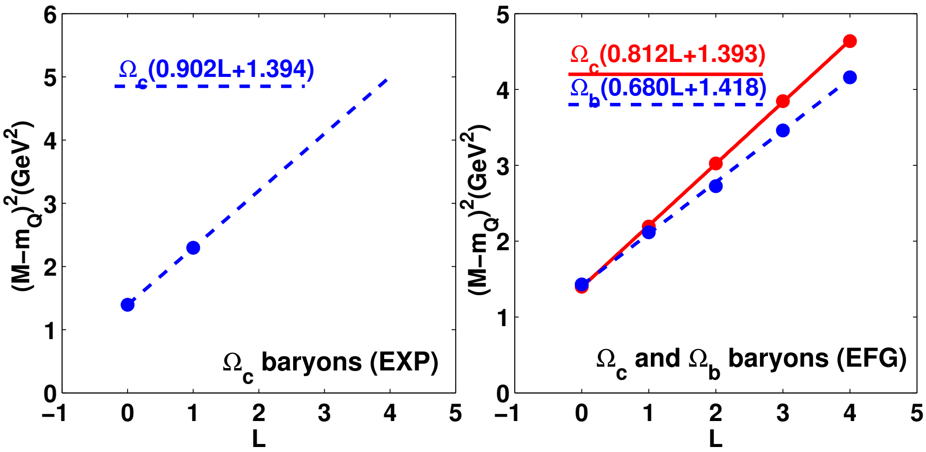

Figure 4: (color online). Plots of experimental data for Ω_c baryons and model calculation results [3] of Ω_Q baryons. The best fit lines are given with equations.

should consider flux energies instead of hadron masses to relate them with an angular momentum L.

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