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The quark model and b baryons

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ABSTRACT

The recent observation at the Tevatron of $\Sigma_b^{\pm}$ (uub and ddb) baryons within 2 MeV of the predicted $\Sigma_b - \Lambda_b$ splitting and of $\Xi_b^-(dsb)$ baryons at the Tevatron within a few mega electron volts (MeV) of predictions has provided strong confirmation for a theoretical approach based on modeling the color hyperfine interaction. The prediction of $M(\Xi_b^-) = 5790–5800$ MeV is reviewed and similar methods used to predict the masses of the excited states Ξ_b' and Ξ_b^*. The main source of uncertainty is the method used to estimate the mass difference $m_b - m_c$ from known hadrons. We verify that corrections due to the details of the interquark potential and to Ξ_b–Ξ_b' mixing are small. For S-wave qqb states we predict $M(\Omega_b) = 6052.1 \pm 5.6$ MeV, $M(\Omega_b^*) = 6082.8 \pm 5.6$ MeV, and $M(\Xi_b^0) = 5786.7 \pm 3.0$ MeV. For states with one unit of orbital angular momentum between the b quark and the two light quarks we predict $M(\Lambda_{b[3/2]}) = 5929 \pm 2$ MeV, $M(\Lambda_{b[3/2]}) = 5940 \pm 2$ MeV, $M(\Xi_{b[1/2]}) = 6106 \pm 4$ MeV, and $M(\Xi_{b[3/2]}) = 6115 \pm 4$ MeV. Results are compared with those of other recent approaches.

1. Introduction

The first observed baryon with a b quark was the isospin-zero Λ_b, whose mass has recently been well-measured: $M(\Lambda_b) = 5619.7 \pm 1.2 \pm 1.2$ MeV [1]. Its quark content is $\Lambda_b = bud$, where the ud pair has spin and isospin $S(ud) = I(ud) = 0$. Now the CDF Collaboration has observed candidates for $\Sigma_b^{\pm}$ and $\Sigma_b^{*\pm}$ [2] with masses consistent with predictions [3–11]. D0 and CDF have seen candidates for $\Xi_b^- = bsd$

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[12,13]. The more precise CDF mass lies close to a prediction based on careful accounting for wave function effects in the hyperfine interaction [14].

The CDF sensitivity appears adequate to detect further heavy baryons. The S-wave levels of states containing bsu or bsd consist of the $J=1/2$ states $\Xi_b^{(0,-)}$ and $\Xi_b^{\prime(0,-)}$ and the $J=3/2$ states $\Xi_b^{*(0,-)}$. Additional baryonic states containing the b quark include $\Omega_b = bss$ $(J=1/2), \Omega_b^* = bss$ $(J=3/2)$, and orbital excitations of Λ_b and other b-flavored baryons. In this paper, we predict the masses of these states and estimate the dependence of the predictions on the form of the interquark potential, extending a previous application to hyperfine splittings of known heavy hadrons [15]. Two observations based on a study of the hadronic spectrum lead to improved predictions for the b baryons. The first is that the effective mass of the constituent quark depends on the spectator quarks [5], and the second is an effective supersymmetry [8]—a resemblance between mesons and baryons where the anti-quark is replaced by a diquark [16]. Parts of this article have appeared previously in preliminary form [14,17].

We review the predictions for Σ_b and Σ_b^* in Section 2, and discuss predictions for $M(\Xi_b)$ in Section 3, starting with an extrapolation from $M(\Xi_c)$ without correction for hyperfine (HF) interaction and then estimating this correction. In the Ξ_b the light quarks are approximately in a state with $S=0$, while another heavier state Ξ_b' is expected in which the light quarks mainly have $S=1$. There is also a state Ξ_b^* expected with light-quark spin 1 and total $J=3/2$. Predictions for Ξ_b' and Ξ_b^* masses are discussed in Section 4. We estimate the effect of mixing between light-quark spins $S=0$ and 1 in Section 5, and isospin splittings of the Ξ_b family of states in Section 6. Section 7 is devoted to predictions of $M(\Omega_b)$ and $M(\Omega_b^*)$, while Section 8 treats orbital excitations. Comparisons with other approaches are made in Section 9, while Section 10 summarizes.

2. The Σ_b and $\Sigma_b^{*\pm}$ states

The $\Sigma_b^{\pm}$ states consist of a light-quark pair uu or dd (a "nonstrange diquark") with $S=I=1$ coupled with the b quark to $J=1/2$, while in the $\Sigma_b^{*\pm}$ states the light-quark pair and the b quark are coupled to $J=3/2$. The corresponding ud pair in the Λ_b has $S=I=0$. The experimental Σ_b–Λ_b mass differences [2],

$$\begin{aligned} M(\Sigma_b^-) - M(\Lambda_b) &= 195.5^{+1.0}_{-1.0}\,(\text{stat.}) \pm 0.1\,(\text{syst.})\ \text{MeV} \\ M(\Sigma_b^+) - M(\Lambda_b) &= 188.0^{+2.0}_{-2.3}\,(\text{stat.}) \pm 0.1\,(\text{syst.})\ \text{MeV} \end{aligned} \tag{1}$$

with isospin-averaged mass difference $M(\Sigma_b) - M(\Lambda_b) = 192$ MeV, are to be compared with the prediction [5,8] $M_{\Sigma_b} - M_{\Lambda_b} = 194\,\text{MeV}$. Note also:

(1) The mass difference between spin-1 and spin-zero nonstrange diquarks governs the splitting between the spin-weighted average $[2M(\Sigma_b^*) + M(\Sigma_b)]/3$ and the Λ_b,

$$\frac{M(\Sigma_b) + 2M(\Sigma_b^*)}{3} - M(\Lambda_b) = (205.9 \pm 1.8)\ \text{MeV}, \tag{2}$$

where we have used the averages of the differences for $\Sigma_b^{(*)\pm}$. This should be the same as the corresponding quantity for charmed baryons,

$$\frac{M(\Sigma_c) + 2M(\Sigma_c^*)}{3} - M(\Lambda_c) = (210.0 \pm 0.5)\ \text{MeV}, \tag{3}$$

and that for strange baryons,

$$\frac{M(\Sigma) + 2M(\Sigma^*)}{3} - M(\Lambda) = (205.1 \pm 0.3)\ \text{MeV}, \tag{4}$$

where the masses are from Ref. [18], and an average over the Σ isospin multiplet is taken. In each case the dominant source of error is the mass of the $I_3 = 0, J = 3/2$ state, Σ_c^{*+} or Σ^{*0}. The agreement is quite satisfactory.

(2) The charge-averaged hyperfine splitting between the $J=1/2$ and $J=3/2$ states involving the spin-1 nonstrange diquark may be predicted from that for charmed particles: