$\Lambda(1600)$: A strange hybrid baryon

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We use the method of QCD sum rules to investigate a possible hybrid baryon with the quantum numbers of the Λ. Using a current composed of *uds* quarks in a color octet and a gluon, a strange hybrid, the Λ_H, is found about 500 MeV above the Λ, and we identify it as the $\Lambda(1600)$. Using our sigma or glueball model we predict a large branching fraction for the $\Lambda_H \to \Lambda + \sigma(\pi\pi$ resonance), and the experimental search for this decay mode could provide a test of the hybrid nature of the $\Lambda(1600)$.

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I. INTRODUCTION

One of the most important aspects of hadron spectroscopy for providing new information about quantum chromodynamics (QCD) is the identification of hybrid hadrons, mesons, and baryons that have gluonic valence components. These are typical exotics, hadrons that cannot be explained in standard quark models. Since some exotic mesons can be identified by their quantum numbers, a great deal of work has been done on hybrid mesons. Hybrid baryons are more difficult to identify experimentally, although there are clear theoretical definitions. For example, a nonstrange baryon or a baryon with strangeness$=-1$ with three quark components in a configuration with color$\neq 0$, while the three quarks plus gluon have zero color, is certainly a hybrid. Strangeness$=+1$ baryons are exotic, but cannot be characterized as hybrids in the sense that they must involve an antistrange quark rather than valence glue.

There have been theoretical studies of hybrid baryons for two decades, including bag model calculations of nonstrange hybrids [1–3] and of strange hybrids [4], models of the $P_{11}(1440)$ (Roper) resonance as a hybrid [5,6], QCD sum rule studies [7–9], and flux tube models [10,11]. A major problem is to identify the hybrids. Electroproduction [6] and a large decay branching ratio into the sigma π-π resonance [12] have been suggested for tests of the Roper resonance as a hybrid; and possible tests of hybrids related to the flux tube model have been suggested [13]. See the recent review by Barnes [14] for a discussion of hybrid baryons and possible ways to identify them.

In the early bag model studies of nonstrange hybrid baryons [1–3] there was a range of solutions of about 1.5–1.9 GeV for the lightest hybrid. Using a bag model for the study of Λ-like strange hybrid baryons, i.e., using (*udsg*) configurations with the *uds* quarks in a color octet, in Ref. [4] a narrower range of solutions was found with the choice of parameters used, and the authors concluded the lightest Λ-type hybrid might be the three-star $\Lambda(1600)$.

In the present work we use the QCD sum rule method as in Ref. [8] to estimate the mass of the lightest strange baryon with the quantum numbers of the Λ: $J^P=\frac{1}{2}^+, S=-1, I=0$. One advantage of the sum rule method is that the composite field operator, called the current, for the particle, for which we use the symbol Λ_H, is a clearly defined hybrid, with the three quarks having nonzero color. Our conclusion in the present work is that the $\Lambda(1600)$ is a hybrid. The theoretical calculation is similar to that of our previous work in which we concluded that the Roper is a good hybrid baryon candidate. Note that the excitation energy of the $P_{11}(1440)$ resonance above the nucleon is similar to that of the $\Lambda(1600)$ above the Λ. We also use the arguments of Ref. [12] to suggest a test of the $\Lambda(1600)$ as a hybrid.

II. QCD SUM RULE ESTIMATE OF THE MASS OF THE Λ_H

The current operator for the Λ_H that we use is the form used in Ref. [8] modified for strangeness:

$$\eta_{\Lambda H}=\epsilon^{abc}[u^a(x)C\gamma^\mu d^b(x)]\gamma^\alpha G^e_{\mu\alpha}(x)\left(\frac{\lambda^e}{2}s(x)\right)^c, \quad (1)$$

where (a,b,c,e) are color indices, λ^e is the generator of the SU(3) color group, (u,d,s) refer to up, down, and strange quarks, and $G_{\mu\nu}=\partial_\mu A_\nu-\partial_\nu A_\mu-ig[A_\mu,A_\nu]$ is the gluonic tensor, with $A_\mu=A^n_\mu\lambda^n/2$ the color field. The corresponding correlator is

$$\begin{aligned}\Pi_{\Lambda H}(x)&=\langle 0|T[\eta_{\Lambda H}(x)\overline{\eta}_{\Lambda H}(0)]|0\rangle\\&=\epsilon^{abc}\epsilon^{a'b'c'}\gamma_5\gamma_\alpha S^{ee'}_s(x)\gamma_\beta\gamma_5\\&\quad\times\langle 0|G^m_{\mu\alpha}(x)G^n_{\nu\beta}(0)|0\rangle\frac{\lambda^m_{ce}}{2}\frac{\lambda^n_{c'e'}}{2}\\&\quad\times\mathrm{Tr}[S^{aa'}_u{}^*(x)C\gamma^\mu S^{bb'}_d(x)\gamma^\nu C], \end{aligned} \quad (2)$$

where S_f is the flavor *f* quark propagator and C is the charge conjugation operator. The correlator has two independent terms, which in momentum space can be written as

$$\begin{aligned}\Pi(q)_{\Lambda H}&=i\int e^{iqx}\langle 0|T[\eta(x)\overline{\eta}(0)]|0\rangle\\&=\Pi_1(q^2)\not{q}+\Pi_2(q^2),\end{aligned} \quad (3)$$

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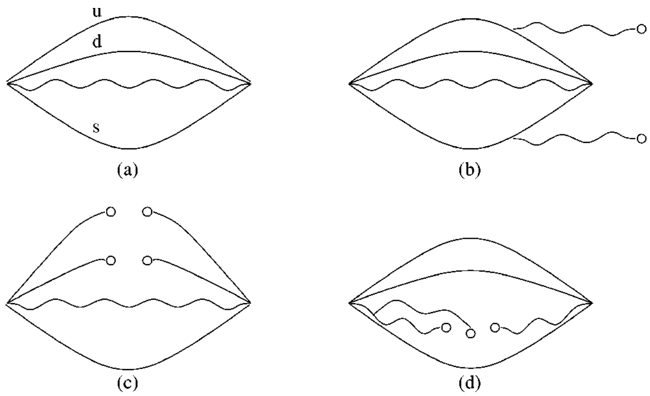

FIG. 1. Diagrams for $\Pi_1(q^2)$ for the OPE including dimension 6 condensates.

with $\not{q}=\gamma_\mu q^\mu$.

The QCD sum rule calculation is very similar to that in Refs. [8,9]. The operator product expansion (OPE) converges rapidly at high $Q^2=-q^2$, which is achieved via a Borel transform. The diagrams included for $\Pi_1(q^2)$ are shown in Fig. 1, and the diagrams included for $\Pi_2(q^2)$ are shown in Fig. 2.

One finds from the diagrams of Fig. 1 that

$$\Pi_1(Q^2)=\frac{1}{45\pi^6}Q^8\ln(Q^2)-\frac{17}{36\pi^5}\langle 0|\alpha_s G^2|0\rangle \times Q^4\ln\left(Q^2+\frac{512}{9\pi^2}\langle 0|\bar{q}q|0\rangle^2 -\frac{2}{3\alpha_s\pi^5}\langle 0|g^3fG^3|0\rangle\right)Q^2\ln(Q^2), \tag{4}$$

and from the diagrams of Fig. 2 that

$$\Pi_2(Q^2)=\frac{16}{9\pi^4}\langle 0|\bar{s}s|0\rangle Q^6\ln(Q^2) -\frac{20}{\pi^4}\langle 0|\bar{q}\sigma\cdot Gq|0\rangle Q^4\ln(Q^2), \tag{5}$$

where $Q^2=-q^2$, and for the condensates the values used are as follows: quark condensate $\langle 0|\bar{q}q|0\rangle=-(0.25)^3$ GeV^3, mixed condensate $\langle 0|\bar{q}\sigma\cdot Gq|0\rangle=0.8(0.25^3)$ GeV^5, gluon

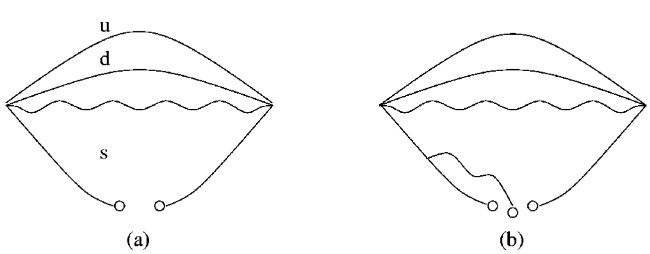

FIG. 2. Diagrams for $\Pi_2(q^2)$ for the OPE including dimension 5 condensates.

condensate $\langle 0|\alpha_s G^2|0\rangle=0.038$ GeV^4, and triple gluon condensate $\langle 0|g^3fG^3|0\rangle=(0.6)^6$ GeV^6. The convention of Ref. [7] has been used. In deriving Eqs. (4), (5) the quark masses have been neglected. Also, the strange quark condensate $\langle 0|\bar{s}s|0\rangle$ is expected to be about 20% smaller than the u,d quark condensates, but this difference is neglected as it does not change our results significantly.

The sum rule method involves equating the dispersion relation for the correlator to the form obtained from the OPE expansion, and using a Borel transform to ensure that the OPE converges rapidly and that the continuum contribution to the dispersion relation is not too large to find the mass given by the pole term. For our problem we must take into account that the Λ as well as the Λ_H can contribute to the correlator given by Eqs. (1), (2), since the Λ can have a ($udsg$) component. Thus the form of the dispersion relation for the correlator, called the phenomenological side of the sum rule, is

$$\Pi_1^{phen}(Q^2)=\frac{c_1}{Q^2+M_\Lambda^2}+\frac{c_2}{Q^2+M_{\Lambda H}^2}+\text{continuum},$$
$$\Pi_2^{phen}(Q^2)=\frac{c_1M_\Lambda}{Q^2+M_\Lambda^2}+\frac{c_2M_{\Lambda H}}{Q^2+M_{\Lambda H}^2}+\text{continuum}. \tag{6}$$

After the Borel transform, in which the Q^2 variable is replaced by the Borel mass M^2, the phenomenological side becomes

$$\Pi_1^{phen}(M^2)=c_1e^{-M_\Lambda^2/M^2}+c_2e^{-M_{\Lambda H}^2/M^2}+\text{continuum},$$
$$\Pi_2^{phen}(M^2)=c_1M_\Lambda e^{-M_\Lambda^2/M^2}+c_2M_{\Lambda H}e^{-M_{\Lambda H}^2/M^2}+\text{continuum}. \tag{7}$$

The constants c_1,c_2 in Eq. (6) contain important information about the wave function, but can be eliminated in the analysis by using the technique of Ref. [8]. The continuum is approximated by replacing the Borel transform

$$\mathcal{B}_{Q^2\to M^2}(Q^{2l}\ln Q^2)=-l!M^{2(l+1)} \tag{8}$$

by

$$\mathcal{B}^c_{Q^2\to M^2}(Q^{2l}\ln Q^2)=-M^{2(l+1)} \times\left(1-\sum_{n=1}^{l}\frac{(s_t/M^2)^n}{n!}e^{-s_t/M^2}\right), \tag{9}$$

where s_t is the threshold $E^2_{c.m.}$, which is chosen by matching the phenomenological to the theoretical expression for the correlator.

The mass of the hybrid is obtained from the expression

$$M_{\Lambda H}=\frac{(d/dM^2)[\Pi_2(M^2)e^{M_\Lambda^2/M^2}]}{(d/dM^2)[\Pi_1(M^2)e^{M_\Lambda^2/M^2}]}. \tag{10}$$

A. Sum rule analysis

The sum rule analysis is essentially identical to that in Ref. [8]. The main errors are in the dependence on the continuum parameter and the uncertainty in the value of the mixed quark condensate. As shown in the figures in Ref. [8] the sum rules for Π_1 and Π_2 are quite stable, and the solution gives a hybrid mass about 500 MeV above the Λ mass. An error of about 15–20 % is expected in this mass difference with this method. Therefore we conclude that

$$M_{\Lambda H} \simeq 1600 \pm 200 \ \text{MeV}, \tag{11}$$

and that the $\Lambda(1600)$ is our candidate for the lightest strange hybrid, with the quantum numbers of the $\Lambda(1116)$. It is also important to consider the sum rule analysis for the $\Lambda(1116)$. Using the current

$$\eta_\Lambda = \epsilon^{abc}[u^a(x) C \gamma^\mu d^b(x)] \gamma_5 \gamma_\mu s(x)^c, \tag{12}$$

it was shown [16] that the $\Lambda(1116)$ mass could be obtained from the two-point correlator

$$\Pi_\Lambda(x) = \langle 0 | T[\eta_\Lambda(x) \overline{\eta}_\Lambda(0)] | 0 \rangle \tag{13}$$

within the expected range. For the correct ordering of baryons, the strange quark condensate $\langle 0|\overline{s}s|0\rangle$ should be about 5% less than the normal quark condensate. The value of $\langle 0|\overline{s}s|0\rangle$ adds uncertainty to our result which has been included in the estimate of Eq. (11). It should also be noted from our study of the Roper as a hybrid that the $\Lambda(1600)$ is almost a pure hybrid and the $\Lambda(1116)$ has little hybrid component, which makes the sum rule method for finding the lowest state for each independent current more reliable. On the other hand, it also causes a limitation of the sum rule method: since the current η_{Λ_H} couples very weakly to the $\Lambda(1116)$, the correlator defined by η_{Λ_H} or the mixed Λ_H-Λ correlator cannot be used to check the QCD sum rule method for estimating the mass of the $\Lambda(1116)$.

III. THE σ DECAY OF THE Λ_H

A test of the hybrid nature of the $\Lambda(1600)$ follows from our glueball or sigma model [15,17]. In studies of scalar hadrons, the mixing of scalar mesons and scalar glueballs was found to be important for mesons and glueballs with masses above 1 GeV. Moreover, a light glueball solution was obtained with a mass 300–600 MeV, which is the mass of the broad $I=0$, $L=0$ π-π resonance found in an analysis of π-π scattering [18], which we call the sigma. If higher dimensional condensates are dropped the light glueball is not found, as in quenched lattice calculations. This leads to our glueball or sigma model, a model based on a coupled channel picture with the glueball pole driving the π-π resonance, motivated in part by the large branching ratios for decays of glueball candidates into channels with sigmas [19]. This model successfully explains [20] the observed [21] D^+ charm meson decay into a $\sigma(\pi\pi)$ resonance, while this decay channel is not found for the D_s^+ decay.

Using the current operator for the Λ, η_Λ of Eq. (12), the decay of the Λ_H into a Λ and a sigma can be estimated by the external field method [22] from the Λ_H,Λ two-point function in an external sigma field:

$$\Pi(q)_{\Lambda\Lambda_H} = i \int e^{iqx} \langle 0 | T[\eta_\Lambda(x) \overline{\eta}_{\Lambda H}(0)]_{J_\sigma} | 0 \rangle, \tag{14}$$

where J_σ is the sigma current. For example, if one were investigating the decay into the pion channel, which is a forbidden $\Lambda_H \to \Lambda$ decay, the current would be $J^\pi = i\overline{q}\gamma_5 q$.

The glueball sigma model leads to the evaluation of the sigma-gluonic coupling

$$\langle G^a_{\mu\nu} J_\sigma G_a^{\mu\nu} \rangle = g_\sigma \langle G^a_{\mu\nu} G_a^{\mu\nu} \rangle. \tag{15}$$

The sigma-glue coupling constant g_σ was estimated from the 356 MeV width of the $\sigma(\pi\pi)$ resonance [18] to be $g_\sigma \simeq 700$ MeV. Because of the unknown constants in the sum rule calculation one can predict only ratios of decay widths. For the study of the Roper as a hybrid we were able to predict the ratio of the sigma decay width to the pion decay width. Since the only decay channels that have been measured for the $\Lambda(1600)$ are $\Lambda(1600) \to N\overline{K}$ and $\Lambda(1600) \to \Sigma\pi$, and the single-pion + Λ channel is not allowed, we are not able to make a specific prediction here. Noting that the decay $P_{11}(1440) \to N + (\pi\pi)_{I=0,L=0}$ has a 5–10 % branching fraction, we predict a sizable $\Lambda_H \to \Lambda + \sigma$ branching fraction. The main background will be the nonresonant π-π channels, so that for the sigma channel the $(I=0, L=0)$ resonance must be extracted. Also, it would be difficult to measure the ratio $\Lambda_H \to \Sigma\sigma / \Lambda_H \to \Sigma\pi$, for which our model could give a prediction, since there is very little phase space to map out to extract the σ resonance due to the mass of the Σ. We can make a rough estimate of the partial width for the $\Lambda_H \to \Lambda + \sigma$ decay by assuming it is similar to that of the Roper to the nucleon-σ channel, which we estimate to be 20–40 MeV.

In conclusion, I believe that a careful experimental study of the $\Lambda(1600) \to \Lambda\pi\pi$, with an analysis to extract the sigma resonance, could be a valuable test of the hybrid nature of this resonance. There have been no experiments on $\Lambda(1600)$ decays for the past 20 years, and this resonance is an excellent candidate for a strange hybrid baryon.

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