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Hybrid baryons via QCD sum rules

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Hybrid baryons, consisting of the three light quarks and a gluon, are investigated using the QCD sum rule method. We find that the mixed condensate $\langle 0|\bar{\psi}\sigma G\psi|0\rangle = m_0^2\langle 0|\bar{\psi}\psi|0\rangle$ plays a dominant role in hybrid baryons in contrast with the quark condensate in the nucleon case. For the standard value of $m_0^2 = 0.8$ GeV^2, the mass of the lowest hybrid state is found to be approximately 1.5 GeV, about the observed mass of the Roper resonance.

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One of the important predictions of QCD is the existence of so-called exotic hadrons, in which the gluonic degrees of freedom play an explicit role. The theoretical and experimental investigations to isolate such states, which have been carried out for some time [1], are concentrated in two areas. The first is to search for "extra" states with quantum numbers that cannot be explained by the conventional quark potential models. For example, in the meson sector a $q\bar{q}G$ state may have $J^{PC}=1^{-+}$, which cannot be constructed from $q\bar{q}$ alone. The second aspect involves a study of the transition properties, such as selection rules [2], which might provide us an experimental signature of gluonic degrees of freedom. The recent investigations [3,4] of the electromagnetic transitions of baryon resonances have shown that there is good evidence that gluonic degrees of freedom might play an active role. In particular, the photo and electroproduction amplitudes for the Roper resonance $P_{11}(1440)$ and the resonance $P_{33}(1600)$ show [4,5] very different behaviors for hybrid $qqqG$ and normal qqq models, which can be tested in the Continuous Electron Beam Accelerator Facility (CEBAF) experiments. Moreover, hybrid pictures for the resonances $P_{11}(1440)$ and $P_{33}(1600)$ may help us to understand the longstanding puzzle that the masses of these resonances are lower than expected [6] in the conventional quark model.

However, the nature of hybrid baryons, as well as their spectrum, are not well understood theoretically. The studies of hybrid states in phenomenological quark models, such as the bag model [7] and quark potential models [8], estimate the mass of the ground hybrid state to be around 1.7 GeV. More recently, the QCD sum rule method [9] has been widely used in hadron spectroscopy. In an early application [10] it was shown that the method predicts masses of the nucleon and other baryons which are consistent with experiment. For a review of the method and the work using QCD sum rules before 1985 see Ref. [11]. The QCD sum rule technique establishes a direct connection between the bound state problem and QCD, and has been quite successful in describing mesons as well as baryons.

The studies of the mass of hybrid mesons using the QCD sum rule method [12] have concentrated on the exotic quantum number $J^{PC}=1^{-+}$. The investigation of hybrid baryons with quantum numbers $J^P=1/2^+$, $I=1/2$ by QCD sum rules was done by Martynenko [13], who concluded that the mass of the ground hybrid baryons is around 2.1 GeV. However, unlike the hybrid meson case, the current operator for the hybrid states has the same quantum number as that for nucleons; thus it is unavoidable that there are some contaminations from the contributions of nucleons. The calculations by Braun *et al.* [14] using QCD sum rules show that the gluonic component in the nucleon is very significant. Therefore, analysis of the sum rules for hybrid baryons with quantum numbers $J^P=1/2^+$, $I=1/2$ without considering the nucleon contributions might be inconsistent.

The focus of the present paper is to give an improved calculation using QCD sum rules for hybrid baryons, with the suppression of the contributions of the nucleon. We find that the mass of the ground state $J^P=1/2^+$, $I=1/2$ hybrid baryons is approximately 1.5 GeV, about the observed mass of the $P_{11}(1440)$.

The current operator for the $J_P=1/2^+$, $I=1/2$ hybrid states is not unique. Various forms have been discussed in Refs. [13,14]. We use the form

$$\eta(x)=[u^a(x)C\gamma^\mu u^b(x)]\gamma^\sigma G^d_{\mu\sigma}(x)[T^d d(x)]^c\epsilon^{abc}, \quad (1)$$

which was also used in Ref. [13], where $u(x)$ and $d(x)$ are operators of the u and d quarks, $G^d_{\mu\sigma}(x)$ is a gluon field strength, $a,b,c=1,2,3$ are the color indices, C is the charge conjugation matrix, and $T^d=\lambda^d/2$ is the generator of the SU(3) color group. The resulting correlations of the current operator in Eq. (1) lead to two independent invariant functions:

$$\Pi^{\alpha\beta}(q)=i\int e^{iqx}\langle 0|T[\eta^\alpha(x)\bar{\eta}^\beta(0)]|0\rangle$$
$$=\Pi_1(q^2)\hat{q}^{\alpha\beta}+\Pi_2(q^2)\delta^{\alpha\beta}, \quad (2)$$

where $\hat{q}^{\alpha\beta}=(\gamma_\mu)^{\alpha\beta}q^\mu$.

The coefficients of the operator product expansion (OPE) are calculated to dimension 6. Thus, in addition to the leading perturbative contribution, the nonperturbative contributions are proportional to the first and second power of the quark condensates $\langle 0|\bar{\psi}\psi|0\rangle$, to the gluon condensate $\langle 0|\alpha_s G^2/\pi|0\rangle$, to the mixed condensate $\langle 0|\bar{\psi}\sigma G\psi|0\rangle$, and to the triple gluon condensate $\langle 0|g^2fG^3|0\rangle$. We use the factorization of the four quark vacuum matrix elements [9] assuming vacuum state dominance. The calculation is fairly standard, and carried out in the x representation, in which the light quark and gluon propagators can be written as

$$S^{ab}(x)=i\frac{\hat{x}}{2\pi^2x^4}\delta^{ab}-ig(T_c)^{ab}G^c_{\mu\nu}(0)\frac{\hat{x}\sigma^{\mu\nu}+\sigma^{\mu\nu}\hat{x}}{32\pi^2x^2}+S^{ab}_{np}(x) \quad (3)$$

and

$$D^{ab}_{\mu\nu}(x)=g_{\mu\nu}\delta^{ab}\frac{1}{4\pi^2x^2}+\frac{gf^{abc}G^c_{\mu\nu}(0)}{8\pi^2}\ln(-x^2), \quad (4)$$

where $\hat{x}=\gamma_\mu x^\mu$, f^{abc} is the structure constant of SU(3) symmetry, $\sigma^{\mu\nu}=i[\gamma^\mu,\gamma^\nu]/2$, and $S^{ab}_{np}(x)=\langle 0|T[\bar{q}^a(x)q^b(0)]|0\rangle$ is the nonperturbative part of the propagator evaluated by the OPE in terms of the condensates. The resulting invariant functions $\Pi_{1,2}(q^2)$ are

$$\Pi_1(q^2)(16\pi)^4=\frac{256}{15\times 24\pi^2}(-q^2)^4\ln(-q^2)-\frac{272}{18}\langle 0|\alpha_sG^2/\pi|0\rangle(-q^2)^2\ln(-q^2)+\left(\frac{16384\pi^2}{9}\langle 0|\bar{\psi}\psi|0\rangle^2-\frac{64}{3\pi\alpha_s}\langle 0|g^3fG^3|0\rangle\right)(-q^2)\ln(-q^2) \quad (5)$$

and

$$\Pi_2(q^2)(16\pi)^4=\frac{1024}{18}\langle 0|\bar{\psi}\psi|0\rangle(-q^2)^3\ln(-q^2)-320\langle 0|\bar{\psi}\sigma G\psi|0\rangle(-q^2)^2\ln(-q^2), \quad (6)$$

in which the coefficients for the gluon, the triple gluon, and the mixed condensate are different from the results obtained by Martynenko although the Feynman diagrams in both calculations are the same. The most significant difference is the coefficient of the gluon condensate term in Π_1, which differs in sign and a factor of 1/2 from the corresponding term in Ref. [13].

Furthermore, the contributions from the nucleon are included in our calculations. As we show below, this is essential for a reliable analysis of the hybrid mass. Thus, the phenomenological side of the sum rules can be written as

$$\mathrm{Im}\Pi_1(s)=\pi\lambda^2_{NG}M^4_N\delta(s-M^2_N)+\pi\lambda^2_GM^4_G\delta(s-M^2_G)+\text{continuum} \quad (7)$$

and

$$\mathrm{Im}\Pi_2(s)=\pi\lambda^2_{NG}M^5_N\delta(s-M^2_N)+\pi\lambda^2_GM^5_G\delta(s-M^2_G)+\text{continuum}, \quad (8)$$

where λ_{NG} and λ_G are the coupling constants for the gluonic component of the nucleon and the hybrid baryons, respectively. Note that λ_{NG}, whose magnitude compared to λ_N of the usual QCD sum rule calculations for the nucleon is of great interest, will be eliminated in the present calculation. We shall evaluate it in future work. The contributions from the higher excited states can be suppressed by the Borel transformation; however, the contributions from the nucleon are important after the Borel transformations. The continuum in Eqs. (7) and (8) are defined as θ functions multiplied by the imaginary parts of Eqs. (5) and (6). From these equations we obtain the sum rule after the Borel transformation:

$$\Pi_1(M^2)=(\lambda^2_{NG}M^4_Ne^{-M^2_N/M^2}+\lambda^2_GM^4_Ge^{-M^2_G/M^2})(16\pi)^4=\frac{256}{15\pi^2}E_4(s_1/M^2)-\frac{272}{9}\langle 0|\alpha_sG^2/\pi|0\rangle E_2(s_1/M^2)+\left(\frac{16384\pi^2}{9}\langle 0|\bar{\psi}\psi|0\rangle^2-\frac{64}{3\pi\alpha_s}\langle 0|g^3fG^3|0\rangle\right)E_1(s_1/M^2) \quad (9)$$

and

$$\Pi_2(M^2)=(\lambda^2_{NG}M^5_Ne^{-M^2_N/M^2}+\lambda^2_GM^5_Ge^{-M^2_G/M^2})(16\pi)^4=\frac{1024}{3}\langle 0|\bar{\psi}\psi|0\rangle E_3(s_2/M^2)-640\langle 0|\bar{\psi}\sigma G\psi|0\rangle E_2(s_2/M^2), \quad (10)$$

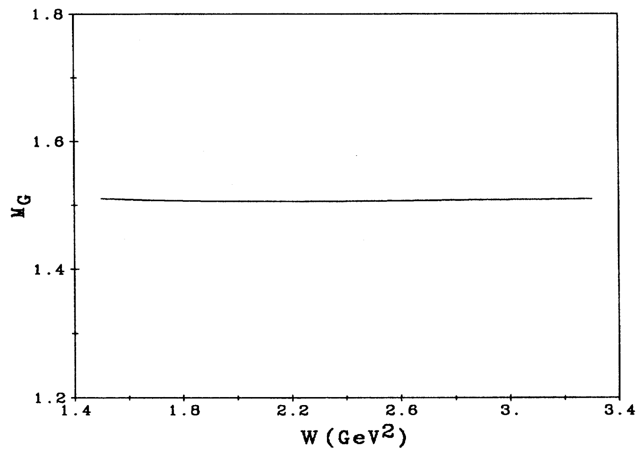

FIG. 1. The mass of the ground hybrid state from the sum rule equation (13), which $m_0^2=0.8$ GeV^2.

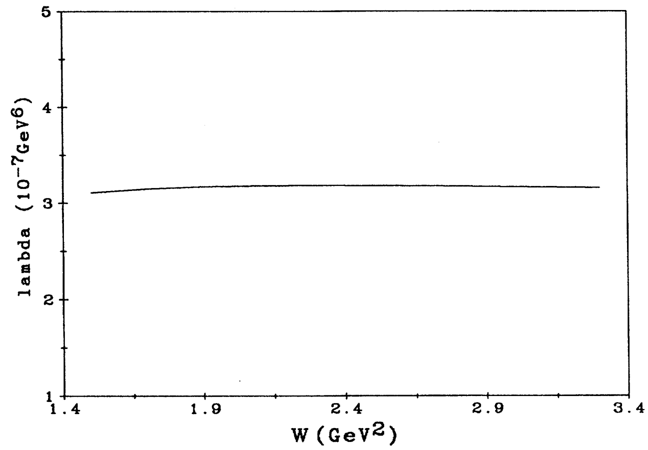

FIG. 2. The coupling constant λ_G^2 in units of 10^{-7} GeV^6 from the sum rule equations (9) and (10).

where M^2 is the Borel parameter, and

$$E_l(r)=M^{2(l+1)}\left(1-\sum_1^l \frac{r^n}{n!}e^{-r}\right). \quad (11)$$

To obtain the mass and the coupling constant of the hybrid states, one has to remove the contributions of the nucleon from the sum rule. If we assume the mass of the nucleon is known, $M_N=0.938$ GeV, we can obtain the following sum rules for the hybrid states after simple derivation:

$$\lambda_G^2 M_G^4 e^{-(M_G^2-M_N^2)/M^2}\frac{M_G^2-M_N^2}{M^2} = M^2\frac{d}{dM^2}[\Pi_1(M^2)e^{M_N^2/M^2}] \quad (12)$$

and similar expression for the sum rule $\Pi_2(M^2)$. Therefore, the mass of the hybrid states is

$$M_G=\frac{\frac{d}{dM^2}[\Pi_2(M^2)e^{M_N^2/M^2}]}{\frac{d}{dM^2}[\Pi_1(M^2)e^{M_N^2/M^2}]}. \quad (13)$$

The standard value of the parameters in Eqs. (9) and (10) are used, $\langle 0|\alpha_s G^2/\pi|0\rangle=0.012$ GeV^4, $\langle 0|\bar\psi\psi|0\rangle=(-0.25)^3$ GeV^3, $\langle 0|g^3 fG^3|0\rangle=(0.6)^6$ GeV^6, $\langle 0|\bar\psi\sigma G\psi|0\rangle=m_0^2\langle 0|\bar\psi\psi|0\rangle$, and $m_0^2=0.8$ GeV^2 (we have followed the convention of Ref. [13], which differs from that of Ref. [10]). The numerical results for the mass of hybrid states are shown in Fig. 1, and the coupling constant is shown in Fig. 2. They are obtained in the region of the resonance $M^2\approx M_G^2$. The resulting mass of the ground hybrid baryon is around 1.5 GeV, and the corresponding threshold parameters are found to be $s_1=2.80$ GeV^2 and $s_2=2.95$ GeV^2. These parameters, which are needed for the evaluation of the functions E_l used to account for the continuum contributions [see Eqs. (9) and (10)] have the values expected for the extraction of the pole term at 1.5 GeV.

As we discussed above, the differences in our work from that of Ref. [13] are our correction of errors in certain Wilson coefficients and our analysis that includes a gluonic component of the nucleon. The major reason that our results differ from those in Ref. [13], is the contribution from the nucleon to the sum rule; and our calculation shows that the resulting hybrid mass would be significantly higher if the contribution from the nucleon is not included. As a consequence, we predict that the lowest hybrid state is in the second resonance region rather than in the 2.0 GeV region, and suggests that a major component of the $P_{11}(1440)$ Roper resonance is of a hybrid nature.

The coupling constant of the hybrid states λ_G^2 is around 3.1×10^{-7} GeV^6. Our value for λ_G^2 is much smaller than the corresponding parameter of the nucleon, which typically [10] has a value of $\lambda_N^2\simeq 2-3\times10^{-4}$. This is a very important result for future studies of possible experimental tests of the picture which emerges from the present analysis: that the Roper resonance might be mainly a hybrid baryon.

Notice that the quark condensate in the invariant function $\Pi_2(M^2)$ gives a negative contribution; thus, the mixed condensate, $\langle 0\bar\psi\sigma G\psi|0\rangle$, plays a very important role in determining the properties of the hybrid baryons. Therefore, they are very sensitive to the parameter m_0^2, which is not well understood compared to the quark condensate. If we increase m_0^2 from 0.8 to 1.0 GeV^2, the resulting mass of the ground hybrid state is found to be 1.8 GeV. Therefore, the uncertainty due to the relatively unknown parameter m_0^2 is significant. The terms that depends on the current quark masses can also be evaluated and we find that the current quark masses only lead to order of 10 MeV corrections, which is within the uncertainty of the sum rule. As seen from the figures, we find stable solutions and expect that our results have a 15–20 % accuracy typical of sum rule mass calculations, with the largest uncertainty being the m_0^2 parameter.

Our result is quite interesting and significant: it supports the possibility of the Roper resonance $P_{11}(1440)$ as a hybrid state. Further studies of the electromagnetic transitions within the framework of the QCD sum rules are needed in order to provide possible experimental signatures of hybrid states. For consistency this must be carried out with both the nucleon and the Roper treated with mixed hybrid and standard baryon currents. This work is in progress. We expect that future experiments at CEBAF will give a definite answer about the existence of the hybrid states.

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