Perturbative QCD Signatures of Hybrid Hadrons in Electroproduction at High Q^2

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In the perturbative domain of quantum chromodynamics, transverse electroproduction of hybrid baryons is small. Their longitudinal electroproduction has size and scaling behavior like normal baryons. Thus deep inelastic scattering has a hybrid resonance peak to background ratio that is small for the transverse structure function but normal size and constant for the longitudinal one. This signature can test if the Roper resonance is a hybrid. Related high-momentum-transfer signatures may clarify the structure of possible nonstandard states such as $\Lambda(1405)$, $f_0(975)$, or $a_0(980)$.

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A hybrid hadron is one whose lowest significant Fock component contains a gluon. Such a gluon is often called a "valence gluon." States with valence gluons, viz., hybrid mesons [1], hybrid baryons [2], or glueballs [3], ought to exist, if QCD is the correct theory of strong interactions. A definite find of a hybrid or glueball would be very important in understanding the strong interaction region of QCD. A problem in isolating states with valence gluons is that they mix with ordinary hadron states. Thus, a hybrid hadron may have a normal three-quark (quark-antiquark) Fock component, albeit with smaller probability.

There has been a suggestion that the Roper resonance $N(1440)$ is a hybrid [4]. The idea explains why the Roper mass is unexpectedly light [5] and suggests that the nucleon to Roper electromagnetic transition is small [6] for low-Q^2 photons.

This paper studies, for the Roper and for other hadrons, how to distinguish a hadron that is a hybrid or a molecular configuration from one that is a basic three-quark or quark-antiquark state, using the behavior of its production rate at high momentum transfer.

Spotlighting one case, we show that hybrid baryon electroproduction will fall relative to background at high Q^2. This is in contrast to q^3 (three-quark) baryons, barring what one can call accidents of the wave function [7], whose resonance peak to background ratio is nearly constant [8,9] as Q^2 changes. The results follow from an application of QCD counting rules [10] for the asymptotic behavior of the form factor for a given hadron Fock component, and of those for the background. The q^3 Fock component normally has a form factor that gives an electroproduction rate falling with the same power of Q^2 as the background. However, for a hybrid the main q^3G component leads to an electroproduction rate falling faster by a factor $O(1/Q^2)$.

We first attempt an estimate of hybrid baryon electroproduction rates. Let α^2 and $1-\alpha^2$ be the relative probabilities of the normal baryonic component and of the pure hybrid component, respectively, and take at $Q^2=0$ the contribution of each component to the hybrid form factor as proportional to its probability. Then, using dipole form-factor mass scale, and omitting factors of $\ln Q^2$,

$$G_+(Q^2)=\text{const}\times\left(\frac{\alpha^2}{[1+Q^2/(0.71\ \text{GeV}^2)]^2}+\frac{1-\alpha^2}{[1+Q^2/(0.71\ \text{GeV}^2)]^3}\right)[Q^2+(m_R-m_N)^2]^{1/2},$$
$$G_0(Q^2)=\text{const}\times\frac{1}{[1+Q^2/(0.71\ \text{GeV}^2)]^2}. \tag{1}$$

Here, the helicity amplitudes or form factors are G_+, G_0, and G_-; when the nucleon has positive helicity, the subscript is the virtual photon helicity in the $\gamma^*N\to R$ Breit frame. The transverse amplitude G_+ has nominally the slowest asymptotic falloff. Up to a Q-independent factor, it is the same as $A_{1/2}$. For the elastic case, it is $Q/m_N\sqrt{2}$ times the magnetic form factor G_M. The square root in (1) gives the known kinematic zero for the $N\to\frac{1}{2}^+$ and $N\to\frac{3}{2}^+$ transitions [11], and also gives G_+ the correct $1/Q^3$ asymptotic falloff for a normal baryon [12]. A pure hybrid G_+ falls like $1/Q^5$, as is explained below. Relaxing the use of a dipole mass scale affects the estimated size of the contributions at finite Q^2, but not the general conclusions. The mass scales are determined by the sizes of the states and should not differ greatly from each other. The longitudinal form factor G_0 (G_E for the elastic case) is shown to fall asymptotically like $1/Q^4$ for both normal and hybrid baryons [thus the 1 in the numerator is $\alpha^2+(1-\alpha^2)$] [13].

A normal nonhybrid baryon has $\alpha\simeq 1$ and has roughly a constant 1:1 resonance-peak/background ratio in νW_2. Asymptotically, the resonance contribution to νW_2 is

$$\nu W_2^{\text{res}}\propto 2G_0^2+G_+^2+G_-^2. \tag{2}$$

Hence—taking this 1:1 ratio as standard for an ordinary baryon—we have at x_R, referring to the location of a resonance peak, a ratio

$$R=\frac{\nu W_2^{\rm res}(x_R)}{\nu W_2^{\rm bkgd}(x_R)}\approx \alpha^4+\frac{2\alpha^2(1-\alpha^2)}{1+Q^2/(0.71\ {\rm GeV}^2)}+\frac{(1-\alpha^2)^2}{[1+Q^2/(0.71\ {\rm GeV}^2)]^2}+O\left(\frac{1}{Q^2}\right). \quad (3)$$

The first three terms are transverse photon contributions, while the last term is a longitudinal contribution with the asymptotic form indicated.

Genuine hybrids are states with small α. Thus, the resonance-peak/background ratio for a hybrid that is seen at low Q^2 must fall with respect to background and be small at high Q^2. This is a necessary condition for a baryon to be a hybrid. With $\alpha=0$, the hybrid stands less than 4% above background in the transverse structure function when Q^2 is above 3 GeV^2, and it is falling to zero. In νW_2, the longitudinal contribution will dominate, but will still be fairly small and falling like $1/Q^2$. If some candidate hybrid is not seen at low Q^2, one must not expect it to surge to prominence at high Q^2.

We must stress that a small resonance-peak/background ratio, while necessary, is not sufficient for a baryon resonance to be a hybrid. The resonance-peak/background ratio can fall for a nonhybrid due to cancellations that make the leading form factor small. This may explain [7] the falling signal/background ratio observed for the $\Delta(1232)$.

We now describe how to get the asymptotic behavior of the helicity amplitudes for hybrid electroproduction. The asymptotic Q^2 dependence of ordinary baryons is governed by diagrams like Fig. 1(a). The rules for calculating the leading Q dependence require a factor Q for each quark line running through the diagram, a factor $1/Q$ for each internal quark propagator, and a factor $1/Q^2$ for each internal gluon propagator. Quark helicity is conserved to get the leading Q dependence, and there are rules for the photon and gluon helicity [14]. For example, to obtain leading Q dependence when one gluon attaches to a quark, it must be transverse; when two gluons or a gluon and a photon attach to a quark, one must be transverse and the other longitudinal. A violation of any helicity rule multiplies the asymptotic Q behavior by at least one factor of $O(1/Q)$. In ordinary baryons, G_+, G_0, and G_- go asymptotically like $1/Q^3$, $1/Q^4$, and $1/Q^5$, respectively.

Hybrid electroproduction from a nucleon is illustrated in Fig. 1(b) using the nucleon q^3 Fock component or in Fig. 1(c) using the nucleon q^3G Fock component. Formalisms that allow a Fock space description of a hadron, including the light-cone formalism, require the constituents to be on shell. Hence the external gluon lines in Figs. 1(b) and 1(c) must be transverse. If all helicity rules are satisfied, the amplitudes in Fig. 1(b) are asymptotically $O(1/Q^4)$ and those in Fig. 1(c) are $O(1/Q^5)$. For G_+, it is not possible for any of the diagrams exemplified by Fig. 1(b) to satisfy the rules, so at least one more factor of $O(1/Q)$ enters. For G_0, all helicity rules can be satisfied for the Fig. 1(b) amplitudes. In particular, quark helicity is conserved for the longitudinal hybrid production. Collecting results, the helicity amplitudes for ordinary baryon (q^3) and hybrid (q^3G) production satisfy

$$G_+(N\to q^3)\propto 1/Q^3,\quad G_0(N\to q^3)\propto 1/Q^4,$$
$$G_+(N\to q^3G)\propto 1/Q^5,\quad G_0(N\to q^3G)\propto 1/Q^4. \quad (4)$$

The longitudinal amplitude is asymptotically the largest for the hybrid and scales the same as for the ordinary hadron. Quark helicity conservation does not imply hadron helicity conservation if there are valence gluons. In longitudinal electroproduction [15] the hybrid will not fall relative to the background and both aspects of the Bloom-Gilman phenomenon [8] (resonances plus background averaging to the scaling curve [16] and resonance-peak/background ratio being constant [9]) should be valid.

The suggestion that the Roper resonance is a hybrid [4] agrees with the nonappearance of the Roper resonance in high-momentum-transfer electroproduction, in contrast to the 1530 and 1688 MeV resonance bumps

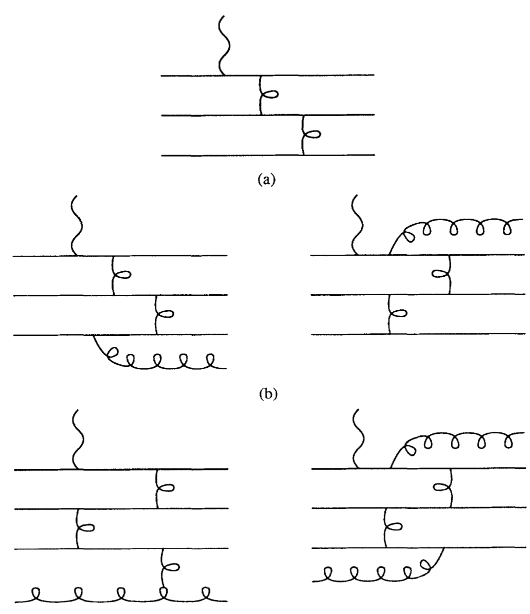

FIG. 1. Examples of lowest-order Feynman diagrams for electroproduction of (a) a three-quark baryon from a nucleon, (b) a pure hybrid (q^3G) baryon from a nucleon; and (c) a pure hybrid baryon from the q^3G Fock component of a nucleon.

that are clearly visible at the same momentum transfers. Earlier data analyses [17] showed a bump at about the Roper mass that grew prominent at 6 GeV^2, the highest Q^2 then shown, but it was not visible below 3 GeV^2. The most recent data [18] have smaller error bars in the few-GeV^2 region and extend to 21 GeV^2 and find no Roper electroproduction.

Our work does not treat low-Q^2 electroproduction, which is in the nonperturbative QCD domain. There are models where the Roper resonance is a $2S$ radial excitation of the nucleon [19] as well as models where it is a hybrid [4]. At high momentum transfers, results based on nonrelativistic wave functions or constituent quark models will not apply. *If the Roper resonance is a hybrid, its electroproduction rate remains small asymptotically, whereas if it is a q^3 state we have no reason for a small electroproduction rate at high Q^2.* Further, if the Roper resonance is a hybrid and its $P_{11}(1710)$ counterpart is a q^3 state, that difference should be reflected in their high-Q^2 electroproduction behavior.

One low-Q^2 SU(6) result is the Moorhouse-Barnes-Close (MBC) selection rule [20], which forbids transitions from the proton, *but not the neutron*, to states with quark-spin-SU(3) configuration $^4\mathbf{8}$. The hybrid Roper resonance can [4,6] overcome this as $^4\mathbf{8}$, and $^2\mathbf{8}$ states may mix. At high Q^2, short-distance wave functions are relevant and spin-dependent forces perturb them drastically from the SU(6) form, as in the Chernyak-Zhitnitsky example [21]. So, even if the MBC rule applies for photoproduction, one should not expect a high-Q^2 suppression of electroproduction for this reason, nor should there be a difference between proton and neutron targets.

Reduced production of hybrids relative to ordinary hadrons at high momentum transfers also occurs elsewhere. Let us take some examples.

The $\Lambda(1405)$ is a state with possible unusual valence quark configurations. It may be a three-quark state with one quark in the P shell [22]. Alternatively, it may be a $\bar{K}N$ bound state [23], minimally a five-constituent object. The true $\Lambda(1405)$ structure may be elucidated by the scaling of its cross section at high momentum transfer. Thus for associated photoproduction of the $\Lambda(1405)$, we get $d\sigma/dt(\gamma N \to K\Lambda(1405)) \propto s^{-7}$, if $\Lambda(1405)$ is a q^3 state, or $\propto s^{-9}$, if $\Lambda(1405)$ is dominantly $\bar{K}N$. (The exponent is 2 minus the number of elementary fields involved [10].) Another prospect is $\Lambda(1450)$ production by a charge-current weak interaction, where the leading leptoproduction form factor for a $\bar{K}N$ state would fall faster than for a q^3 state by $O(1/Q^2)$.

For another example, evidence from spectroscopy and decays suggests the $f_0(975)$ and $a_0(980)$ are $q^2\bar{q}^2$ states [24–26]. Electromagnetic reactions can provide further evidence, as in the sequence $d\sigma/dt(\gamma p \to mN) \propto s^{-7}$, s^{-8}, or s^{-9} for $m = (q\bar{q})$, $(q\bar{q}G)$, or $(q^2\bar{q}^2)$, respectively.

Hybrid or molecular meson scaling behavior is also distinct from that of two-gluon glueballs, which have the same scaling behavior as $q\bar{q}$ mesons. An $O(1/s)$ suppression does apply to three-gluon glueballs.

To summarize, the hybrid hypothesis for the Roper resonance has a perturbative QCD signal. For a pure hybrid baryon, the transverse form factor falls asymptotically $O(1/Q^2)$ faster than what is expected for a normal q^3 baryon. The longitudinal form factor of a hybrid baryon, on the other hand, falls at the same rate as a q^3 baryon. Hence, in electroproduction a pure hybrid falls relative to background by $O(1/Q^4)$ in the transverse structure function and $O(1/Q^2)$ in νW_2.

For a hybrid with some mixture of a q^3 state, there is a small part of the production rate that is constant with respect to background, in addition to another initially larger part that falls like $O(1/Q^2)$ with respect to background. Though this resembles $\Delta(1232)$ electroproduction, the underlying reasons for the two are very different. In the latter there is wave-function accident. Barring that for the Roper resonance, we have a useful rule: *A δ-like Roper resonance is a hybrid.* The exception could be checked in other exclusive processes.

Similar considerations apply to other high-momentum-transfer production processes for hybrids or molecular states. Thus, the scaling of the electromagnetic production rates for $\Lambda(1405)$, $a_0(980)$, or $f_0(975)$ is different depending on whether they are molecular configurations or q^3 or $q\bar{q}$ states.

What momentum transfer is sufficient for asymptotic scaling to be seen? For resonance electroproduction, the nucleon, the 1520-MeV bump, and the 1688-MeV bump appear to scale as expected from perturbative QCD, starting at Q^2 of a few GeV^2 [18]. Hence CEBAF energies may suffice to see the transition from nonperturbative to perturbative electroproduction of hybrid hadrons.

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