Model-Independent Extraction of the $N^*(1535)$ Electrostrong Form Factor from Eta Electroproduction

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(Received 19 July 1996)

We analyze the existing data on electroproduction of eta mesons in the region of $W \approx 1.5$ GeV, and extract an electrostrong form factor for the $N^*(1535)$ electroexcitation and decay into the η-N channel, which is found to be relatively insensitive to the uncertainties of the effective Lagrangian approach. This extracted quantity is of interest in the QCD description of relevant baryons. [S0031-9007(96)01822-4]

PACS numbers: 13.60.Le, 12.40.Vv, 25.30.Rw

One of the basic questions in baryon physics is how an N to N^* electroweak excitation amplitude (N, nucleon, N^*, a nucleon resonance) evolves as a function of the four-momentum transfer squared, $-Q^2$. The real photon point, $Q^2 = 0$, and the region of relatively low Q^2 are clearly the domains of nonperturbative QCD. This region is theoretically difficult to describe, and is currently treated in a variety of QCD-inspired models [1]. Rigorous calculations in the lattice QCD framework [2] are still in the primitive stage. At some high enough Q^2, the value of which is under constant debate, the perturbative QCD scaling rules would set in. Eventually gluon effects would become visible as scaling violations [3]. There is some crude experimental evidence [4] suggesting the onset of scaling around the $4-6\ \mathrm{GeV}^2$ region of Q^2. The high-Q^2 region should also exhibit the phenomenon of the Bloom-Gilman duality [5], which is a relation between the structure functions of the resonance and the deep inelastic regions. All these theoretical expectations provide a dramatic setting for the excited baryon studies at the newer generation "continuous wave" (cw) facilities for electrons, such as CEBAF at the Jefferson Lab, where polarized targets and beams would be available for such studies.

This brings us to the subject of this Letter, the process

$$e + p \rightarrow e' + p + \eta\,, \tag{1}$$

in the region of the cm energy $W \approx 1.5$ GeV, corresponding to the excitation of $N^*(1535)$, the so-called S11 resonance, with $J^\pi I = \frac{1}{2}^- \frac{1}{2}$. A fair bit of data on this reaction exists [6] from the experiments at the older generation accelerators. Some precise real photon studies [7] have been recently done at Mainz. While we await more precise experiments at CEBAF [8], the older data set can already give us valuable insights in the electrostrong amplitude, characteristic of the excitation, and decay of the $N^*(1535)$ resonance. This is what we intend to do here.

Using existing data on (1) and an effective Lagrangian approach [9], we shall show that nearly model-independent inference on the product of the transverse helicity amplitude and the strong decay amplitude is possible. This, together with the study of the strong decay property of the $N^*(1535)$ at hadron facilities like SATURNE [10] and COSY, would eventually allow us to examine the behavior of the transverse helicity amplitude $A_{1/2}$ *alone* as a function of Q^2. The quantity extracted by us is of direct interest to the QCD structure of the relevant baryons, viz., nucleon and $N^*(1535)$.

We note at the outset that the reaction (1) is completely dominated by the $N^*(1535)$ resonance (Fig. 1). This resonance is best looked at via the $\eta-N$ channel, as the latter is rather remarkable in *avoiding* a strong coupling to other N^* states, in contrast to $N\pi$, which exhibits the property for strong coupling to many N^*'s. Thus, the theoretical interpretation becomes much simpler in the $p\eta$ decay of the $N^*(1535)$, in contrast to the $p\pi$ decay channel.

The most general effective Lagrangian for the $\gamma NN^*(1535)$ vertex is, with $R = N^*(1535)$,

$$\mathcal{L}^1_{\gamma NR} = \frac{e}{2(M_R + M)} \bar{R}\big(G_1^s(k^2) + G_1^v(k^2)\tau_3\big) \times \gamma_5 \sigma_{\mu\nu} N F^{\mu\nu} + \text{H.c.}\,, \tag{2}$$

$$\mathcal{L}^2_{\gamma NR} = \frac{e}{(M_R + M)^2} \bar{R}\big(G_2^s(k^2) + G_2^v(k^2)\tau_3\big) \times \gamma_5 \gamma_\mu N \partial_\nu F^{\mu\nu} + \text{H.c.}\,, \tag{3}$$

taking the pseudoscalar coupling at the $\eta NN^*(1535)$ vertex, where $F^{\mu\nu}$ is the electromagnetic field tensor, s and v are superscripts indicating isoscalar and isovector transition form factors, respectively, which are unknown, to be determined from a fit to the existing data [6] on the differential cross section. M_R and M are the relevant baryon masses. The kinematics for the virtual photon four momentum $k = (k_0, \vec{k})$ is the usual one: $k^2 \equiv -Q^2 = (k_1 - k_2)^2 \approx -4E_1E_2 \sin^2\psi/2$, ψ is the electron scattering angle, E_1, E_2, $\vec{k}_1$, $\vec{k}_2$ are energies and

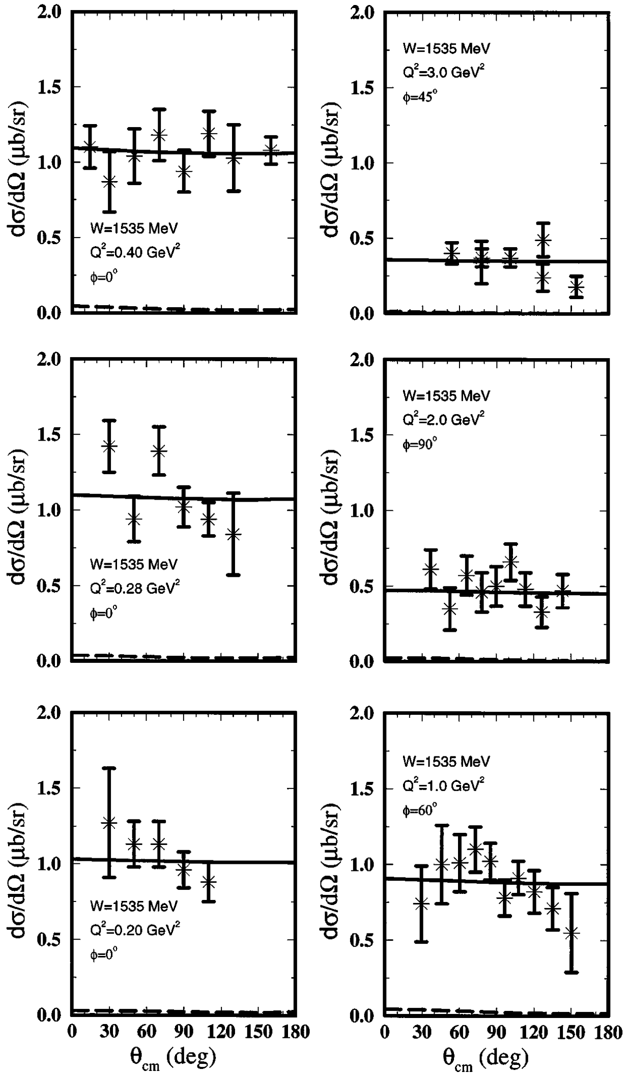

FIG. 1. Angular distributions for eta mesons and our best fits (solid line) in the effective Lagrangian approach. The dashed line is without $N^*(1535)$. The data are from Ref. [6].

momenta of the incident and scattered electrons. The S matrix for the process (1) is

$$S_{fi} = \frac{e}{(2\pi)^7}\delta^4(p_f + k_2 + q - p_i - k_1) \times \sqrt{\frac{m^2M^2}{2\omega E_1E_2E_iE_f}}\, i\mathcal{M}_{fi}\,. \tag{4}$$

Here m is the meson mass; the hadron four momenta are, for the incoming and outgoing nucleons, $p_i = (E_i, -\vec{k})$, $p_f = (E_f, -\vec{q})$, and for the η meson, $q = (\omega, \vec{q})$, in the cm frame of the final nucleon and the meson, defined by $\vec{q} + \vec{p}_f = \vec{k} + \vec{p}_i = 0$. For the lack of space, we omit the Born terms for the nonresonant meson production [9], and give below the expressions for $i\mathcal{M}_{fi}$ for the s-channel excitation of the resonance R, using the Lagrangian in (2) and (3):

$$i\mathcal{M}^1_{fi} = \frac{eg_\eta G^p_1(k^2)}{(M + M_R)}\bar{U}_f \times \frac{\gamma\cdot(p_i + k) + M_R}{s - M_R^2}\gamma_5\gamma\cdot k\gamma\cdot\epsilon U_i\,, \tag{5}$$

$$i\mathcal{M}^2_{fi} = \frac{eg_\eta G^p_2(k^2)k^2}{(M + M_R)^2}\bar{U}_f \times \frac{\gamma\cdot(p_i + k) + M_R}{s - M_R^2}\gamma_5\gamma\cdot\epsilon U_i\,, \tag{6}$$

with g_η, the ηNR coupling, U_i and U_f, the spinors for incoming and outgoing N, $s = W^2 = (E_i + k_0)^2$. Note that the second term vanishes for the real photon. For the u channel, the amplitude can be constructed by crossing symmetry.

The canonical procedure for calculating the differential cross section for the process and polarization observables, is to write $\mathcal{M}_{fi}$ in terms of the CGLN-type [11] amplitude $\mathcal{F}$: $\mathcal{M}_{fi} = (4\pi W/M)\chi_f^\dagger\mathcal{F}\chi_i$, where the χ_i and χ_f are the nucleon Pauli spinors, taking into account the transitions $\gamma N \to N^* \to \eta N$, where γ is the virtual photon. The amplitude $\mathcal{F}$ is given by $\mathcal{F} = i\vec{\sigma}\cdot\vec{b}\mathcal{F}_1 + \vec{\sigma}\cdot\hat{q}\vec{\sigma}\cdot(\hat{k}\times\vec{b})\mathcal{F}_2 + i\vec{\sigma}\cdot\hat{k}\hat{q}\cdot\vec{b}\mathcal{F}_3 + i\vec{\sigma}\cdot\hat{q}\hat{q}\cdot\vec{b}\mathcal{F}_4 - i\vec{\sigma}\cdot\hat{q}b_0\mathcal{F}_5 - i\vec{\sigma}\cdot\hat{k}b_0\mathcal{F}_6$, with $b_\mu = \epsilon_\mu - (\vec{\epsilon}\cdot\hat{k}/|\vec{k}|)k_\mu$. The $\mathcal{F}_i$'s can be converted into helicity amplitudes H_i $(i = 1,\ldots,6)$, in terms of which the differential cross section can be written appropriately:

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_T}{d\Omega} + \epsilon\frac{d\sigma_s}{d\Omega} + \epsilon\cos 2\phi\frac{d\sigma_p}{d\Omega} + \sqrt{2\epsilon(1 + \epsilon)}\frac{d\sigma_I}{d\Omega}\cos\phi\,, \tag{7}$$

wherein various structure functions of the right-hand side can be rewritten in terms of the bilinears of the helicity amplitudes. In (7), ϕ is the azimuth and ϵ is the virtual photon polarization [12]. We can express the helicity amplitudes in terms of the multipole amplitudes as well. In the $N \to N^*(1535)$ case, we have to deal with two helicity amplitudes $A_{1/2}$ and $S_{1/2}$, which can be given in terms of G_1^p and G_2^p in (5) and (6).

Our procedure to fit the existing differential cross-section data [6] is the following. We fix the Born terms for nucleon and vector meson exchanges as in the real photon case [9], except for the form factors. The nucleon form factors have the usual dipole form, while the $\rho\eta\gamma$ and $\omega\eta\gamma$ electromagnetic form factors are parametrized in terms of the prescription of the vector dominance [13]. Thus, $G_{V\gamma\eta}(k^2) = (1 - k^2/m_V^2)^{-1}$, where $m_V \approx \frac{1}{2}(m_\rho + m_\omega)$, the average vector meson mass. It is a reasonable approximation to neglect relatively small contributions from nucleonic resonances, such as D13(1520), to the angular distributions at the crude level of precision of the old data. However, high precision of data expected in new facilities and polarization observables would require their inclusion. With the existing database on electroproduction of etas, it is not possible to extract any meaningful information on other resonances. Given the relative importance of the nucleon Born terms, vector meson exchanges and the excitation of $N^*(1535)$ in the ascending order, we use this model to determine the $A_{1/2}(Q^2)$, given some Ansätze for the small scalar (longitudinal) amplitude $S_{1/2}(Q^2)$. [There are different conventions [14–17] involved in the definition of scalar (or, equivalently, longituginal) helicity amplitude.] Since the current experimental data are not accurate enough to pin down the longitudinal strength of the $S_{11} \rightarrow \gamma + N$ transition, we have chosen three scenarios for the value of the ratio $R_{LT} = S_{1/2}/A_{1/2}$: (a) $R_{LT} = 0$; (b) fix R_{LT} by the quark shell model [15]; (c) use the value of R_{LT} from the works cited as Refs. [14–16] in Stanley and Weber [16]. This gives us a measure of the uncertainty in extracting the tranverse helicity amplitude, given that for the longitudinal amplitude.

In Fig. 1, we show the angular distributions measured [6] in the reaction (1) and our best fits in the effective Lagrangian approach. Notice the dominance of the $N^*(1535)$ excitations: As we turn off the $N^*(1535)$ contribution, the differential cross section collapses completely. Thus, it makes sense to extract the electrostrong property of the $N^*(1535)$ resonance from the process (1).

In Table I, we give the value of the parameter $\xi_T = \sqrt{\chi' \Gamma_\eta} A_{1/2}/\Gamma_T$, where χ' is a kinematic parameter [9], $\sqrt{\Gamma_\eta}/\Gamma_T$ is the $N^* \rightarrow p\eta$ decay amplitude. This parameter [see Ref. [18]] is our extracted electrostrong form factor for the $N^*(1535)$ resonance, of interest to the QCD description of baryons. We note the relative insensitivity of this quantity to a variation of parameters of the model inputs, such as the resonance parameters, value of $g_{\eta pp}$, vector meson form factor, and so on. This is the *central result* of our Letter.

In Fig. 2, we plot ξ_T for different inputs of the $S_{1/2}$ to $A_{1/2}$ ratio. This shows relative insensitivity of the extracted parameter ξ_T to the current experimental and theoretical uncertainties in the extraction of the longitudinal to transverse amplitude ratio. We also include the prediction of a light front approach from Stanley and Weber [16]. The present nonrelativistic versions of the quark model [15], predictions of which are represented by the dot-dashed lines, and the prediction from Stanley and Weber [16] are unable to reproduce the variation of this extracted parameter as a function of Q^2.

In summary, measured angular distributions of the η electroproduction process allow us, in the effective Lagrangian approach, to extract the form factor characteristic of the γpN^* and ηpN^* vertices, which is essentially model independent. The current versions of the quark model, though quite successful in phenomenological terms, are unable to explain the Q^2 dependence of this extracted electrostrong form factor. Thus, we urgently need rigorous nonperturbative calculations using QCD on the lattice.

This work has been done mostly at RPI, where the authors have been supported by the U.S. Department of Energy. The work at Saskatoon has been supported by the Natural Sciences and Engineering Research Council of Canada. One of us (N. C. M.) thanks Dr. B. Saghai for

TABLE I. The fitted results of $A_{1/2}$ and ξ_T for different models ($S_{1/2} = 0$ here). Models 1 and 2 are with different mass positions widths and decay ratios ($W = 1535$ MeV, 1549 MeV, $\Gamma = 150$ MeV, 202 MeV, $\Gamma_\eta/\Gamma = 0.5$ and 0.55, respectively). Model 3 is the result of doubling the η-nucleon coupling constant. Model 4 is the result of change of the cutoff of form factor at vector meson nucleon vertex from 1.2 GeV^2 to 2.0 GeV^2. For each entry the first line is $A_{1/2}$ in units of 10^{-3} GeV$^{-1/2}$ and the second line is ξ_T in units of 10^{-1} GeV^{-1}.

Q^2 (GeV^2)	Model 1	Model 2	Model 3	Model 4
0.0	88.83 ± 7.03	97.27 ± 5.62	87.07 ± 5.44	90.18 ± 5.58
	2.04 ± 0.16	1.90 ± 0.11	2.00 ± 0.12	2.07 ± 0.13
0.2	88.93 ± 5.94	97.28 ± 6.57	89.00 ± 5.97	86.95 ± 6.07
	2.04 ± 0.14	1.90 ± 0.13	2.04 ± 0.14	1.99 ± 0.14
0.28	91.56 ± 5.85	99.99 ± 6.48	91.54 ± 5.88	89.70 ± 5.98
	2.10 ± 0.13	1.95 ± 0.13	2.10 ± 0.13	2.06 ± 0.14
0.4	91.08 ± 5.91	99.27 ± 6.54	90.78 ± 5.95	89.16 ± 6.04
	2.09 ± 0.14	1.94 ± 0.13	2.08 ± 0.14	2.04 ± 0.14
0.6	90.95 ± 8.50	92.79 ± 8.94	88.80 ± 8.59	91.95 ± 8.86
	2.08 ± 0.19	1.81 ± 0.17	2.04 ± 0.20	2.11 ± 0.20
1.0	82.83 ± 7.12	89.93 ± 7.87	82.67 ± 7.16	81.07 ± 7.30
	1.90 ± 0.16	1.76 ± 0.15	1.89 ± 0.16	1.86 ± 0.17
2.0	59.75 ± 7.10	64.65 ± 7.83	59.59 ± 7.14	58.25 ± 7.31
	1.37 ± 0.16	1.26 ± 0.15	1.34 ± 0.16	1.34 ± 0.17
3.0	52.45 ± 5.32	57.04 ± 5.86	52.40 ± 5.33	51.88 ± 5.39
	1.20 ± 0.12	1.11 ± 0.11	1.20 ± 0.12	1.19 ± 0.12

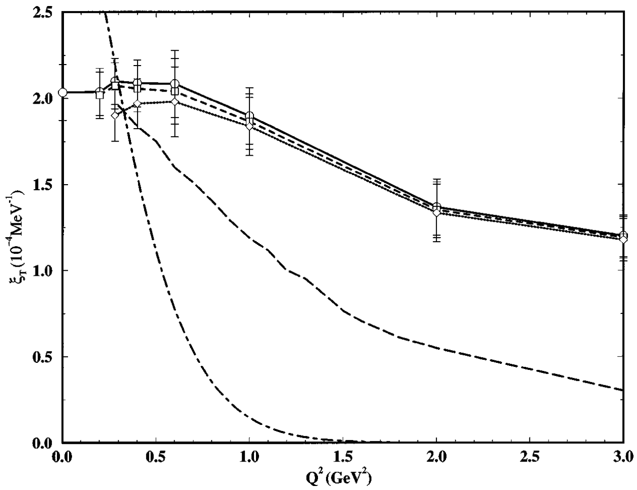

FIG. 2. ξ_T vs Q^2 for different prescriptions of the $S_{1/2}$ to $A_{1/2}$ ratio: (i) set $S_{1/2} = 0$ (circles connected by a solid line); (ii) fix $S_{1/2}/A_{1/2}$ by the quark shell model [15] (squares connected by a dashed line); (iii) use the value of $S_{1/2}$ from Refs. [14–16] of Ref. [16] (diamonds connected by a dotted line). The nonrelativistic quark model prediction of Ref. [15] is the dot-dashed line. The prediction from a light front approach of Stanley and Weber [16] is also shown (long-dashed line) with their parameter $\alpha = 0.2$ GeV^2.

his hospitality at CEN, Saclay, and for many enjoyable discussions.

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