Recently obtained polarized target and photon asymmetry data in eta photoproduction are shown to be very powerful, in conjunction with the differential cross-section data, in yielding model-insensitive constraints on the electrostrong parameters for the excitation and decay of the $N^*(1520)$ resonance. The extracted ratio of its electromagnetic helicity amplitudes, $A^+_2/A^+_{1/2}$, provides a critical test for the QCD-inspired hadron models.

**Keywords:** $\eta$ meson, $N^*(1520)$ and $N^*(1535)$ resonances, Polarization observables, Effective Lagrangian

Studies of the electromagnetic $[3]$ and weak $[2]$ transition amplitudes to various resonance states of the nucleon $(N)$ as a function of the square of the four-momentum transfer, $q^2$, is a powerful way to explore the chromodynamic structure of the nucleon. The real photon point, for which $q^2 = 0$, is one end of the domain of non-perturbative QCD, which continues until some large $q^2$, as yet unknown, which marks the onset of perturbative QCD (pQCD). For the $N \to N^*$ transitions, with the spin of the $N^*$ being $1/2$, there are two helicity amplitudes, $A^+_{1/2}$ and $A^+_{3/2}$, for real photon excitations. In contrast to the pQCD domain, where counting rules yield $A^+_{3/2} \gg A^+_{1/2}$ $[3]$, the non-perturbative region is characterized by a large helicity violation $[1]$. In this Letter, we shall study this in the $N \to N^*(1520)$ real photon transition, via the reaction

$$\gamma + p \rightarrow p + \eta, \quad (1)$$

with the photon lab energy from the eta photoproduction threshold of 707 MeV, up to about 900 MeV, dictated by the availability of data and relative dynamical simplicity.

Though a well-established resonance from the analyses of the pion-nucleon scattering and pion photoproduction, the electromagnetic properties of $N^*(1520)$, are yet to be studied experimentally via complementary reactions such as (1) and fully understood in the framework of the QCD-inspired models. Our interest in the reaction (1) is also enhanced by the recent availability of high quality data from different photon factories: differential cross-section data from the Mainz microtron $[3]$, the polarized target asymmetry (PTA) from the upgraded electron facility at Bonn $[3]$ and a precise data set, just released, on the polarized photon asymmetry (PPA) from the French laser light source, GRAAL $[3]$. We show below that a combination of these observables provide a powerful constraint on relatively small effects from the excitation of the $N^*(1520)$ resonance and its decay, amplified by the interference with the dominant contribution of the $N^*(1535)$ resonance. There are also subtle issues arising from the nodal structures $[3]$ of these observables. Finally, we discuss implications of these data on the non-perturbative QCD violation of the helicity conservation in the electromagnetic process $N \to N^*(1520)$, and in particular, on the testing of various QCD-inspired models $[3]$ of hadrons.

Absent lattice gauge theoretic estimates, our theoretical knowledge of helicity amplitudes for the baryon resonance excitation comes from the QCD-inspired models $[3]$. Current level of their uncertainties for the helicity amplitudes for the $N \to N^*(1520)$ excitation is as follows: the $A^+_{1/2}$ amplitude for the proton target ranges from $-13$ to $-51$, in units of $10^{-3}$GeV$^{-1/2}$, in various versions $[3]$ of the constituent quark model, while the $A^+_{3/2}$ amplitude is predicted to be in the range 117 to 173 in the same units. The 1996 PDG $[3]$ values of these amplitudes from pion photoproduction quote relatively small errors, but they do not include theoretical uncertainties of the position, branching ratios and width of the resonance. The relatively large uncertainties in the partial width $\Gamma_\eta(\sim 0.14$ MeV) of the resonance $N^*(1520)$ to decay into $\eta N$ channel and the total width, $\Gamma$, known to be between 110 to 135 MeV, result in errors in extracting $A_i$ from the photoproduction data, much bigger than the errors quoted by the PDG. An attempt to get these amplitudes from the $(\gamma, \pi\pi)$ reaction has yielded the $A^+_{1/2}$ amplitude only within a factor of two $[10]$, with no meaningful constraint on $A^+_{3/2}$.

We shall extract from the process (1) the parameters $\xi_i (i = \frac{1}{2}, \frac{3}{2})$ defined as $[11]$

$$\xi_i = \sqrt{\chi} \Gamma_\eta A_i / \Gamma, \quad (2)$$

where $\chi$ is a kinematic parameter, $Mk/(qM_R)$, $k$ and $q$ are the photon and eta meson momenta in the $\eta N cm$ frame, $M$ and $M_R$ are the nucleon and the resonance masses. One of our findings is that the new cross-section and polarization data of the reaction (1), taken together, give us precise estimates of the quantities $\xi_{1/2}$ and $\xi_{3/2}$ for $N^*(1520)$ for the first time from the reaction (1).
Thus the quantity $\xi_{3/2}/\xi_{1/2}$ yields an estimate of the ratio of electromagnetic helicity amplitudes $A_{3/2}/A_{1/2}$ essentially independent of uncertainties of the strong interaction parameters, which drop out in the ratio. This is a crucial result of this Letter, of substantial value to distinguish among competing hadron models.

Our theoretical tool for analysis of the reaction (1) is the effective Lagrangian approach, which consists, in the tree approximation of the s- and u-channel nucleon and resonance Born terms and the t-channel vector meson ($\rho$ and $\omega$) exchanges \[11]. Dominant contributions for eta photoproduction around $W \sim 1.3$ GeV are well-studied, consisting of the nucleon Born terms and s-channel excitation of $N^*(1535)$ $\frac{1}{2}^-$, $T = \frac{1}{2}$ resonance \[11,12]. Our goal here is to get at the relatively small contributions from the excitation of $N^*(1520)$, $\bar{\frac{5}{2}}^-$, $T = \frac{3}{2}$ resonance. We cannot do that from the differential cross-section data alone, even though there is a hint \[1,2,3,4\] of its presence from these data. It is a combination of these differential cross-section data with the recently gathered data \[5\] on polarization observables that allows us to put powerful constraints on $N^*(1520)$ amplitudes. The PPA turns out to be rather insensitive to $A_{1/2}$, thereby giving us a better fix on $A_{3/2}$, while the differential cross-section and the PTA help us to constrain the $A_{1/2}$ amplitude.

We shall now briefly discuss the general structure of the interaction Lagrangian for the $\frac{3}{2}^-$, $T = \frac{1}{2}$ resonance excitation. The strong and electromagnetic pieces are \[11\]:

$$L_{\eta NR} = \frac{g_R}{\mu} \bar{R}^\mu \eta R_{\mu}(Z)\gamma_5 N \partial^\nu \eta + h.c.,$$

$$L_{1NR} = \frac{ie}{2M} \bar{R}^\mu \eta R_{\mu}(Y)\gamma_\lambda (G^s_1 + \tau_3 G^c_1)N F_{\lambda \nu} + h.c.,$$

$$L_{2NR} = -\frac{e}{4M^2} \bar{R}^\mu \eta R_{\mu}(X)(G^s_1 + \tau_3 G^c_1)(\partial_\lambda N)F^{\nu \lambda} + h.c.,$$

where the tensor $\theta_{\mu \nu}(A)$ is defined as follows \[11\]:

$$\theta_{\mu \nu}(A) = g_{\mu \nu} - \frac{1}{2}(1 + 2A)\gamma_\mu \gamma_\nu.$$  

Parameter $A$ is not a priori known and it must be determined from the fits to the data on the reaction (1). $R$ is the vector-spinor field for the spin-$\frac{1}{2}$ resonance; the resonant three-point couplings for the proton target, $g_R$, $G^s_1 = G^c_1 + G^s_1$ are all to be determined from the fits to the data of the reaction (1); $F^{\nu \mu}$ is the electromagnetic field tensor representing the external real photon field. In the broadest fit we have attempted, we have nine effective parameters: in the non-resonant part of the amplitude, these are the eta-nucleon coupling and two vector meson couplings; in the resonant sector we have one helicity amplitude for $N^*(1535)$ and two helicity amplitudes $A_{3/2}$, $A_{1/2}$ for $N^*(1520)$ excitation and three “off-shell” parameters, $X, Y, Z$ \[11\]. We use the CERN routine MINUIT \[15\] for these fits. This helps us to get the global $\chi^2$ minimum in the fitting process.

We start with the expressions for the observables of our interest in terms of the helicity amplitudes $H_i (i = 1,2,3,4)$ and write them in terms of multipole amplitudes up to $d$-waves in the $\eta N$ channel \[9\], exhibiting only terms involving the dominant $E_{0+}$ multipole. Thus, the differential cross-section \[9\], the PPA $[\Sigma]$ and the PTA $[T]$ are given by \[9\]:

$$\frac{d\sigma}{d\Omega} = \left| \frac{q}{|k|} \sum_{i=1}^{i=4} H_i \right|^2$$

$$= \left| \frac{q}{|k|} \right| \left[ E_{0+}^2 - 2\cos\theta \text{Re} \left\{ E_{0+}^* (E_{2-} - 3M_{2+} + 3M_{2+} + 6E_{2+}) \right\} + 2\cos\theta \text{Re} \left\{ E_{0+}^* (3E_{1+} + M_{1+} - M_{1-}) \right\} + 3\cos^2\theta \text{Re} \left\{ E_{0+}^* (E_{2-} - 3M_{2-} + 6E_{2+} + 3M_{2+}) \right\} \right].$$

$$= -\left| \frac{q}{|k|} \right| 3\sin^2\theta \text{Re} \left\{ E_{0+}^* (M_{2-} - E_{2+} - M_{2+} - E_{2+}) \right\},$$

$$\frac{d\sigma}{d\Omega} [T] = \left| \frac{q}{|k|} \right| \text{Im} \left\{ H_1 H^*_2 + H_2 H^*_3 \right\} - \left| \frac{q}{|k|} \right| 3\sin\theta \text{Im} \left\{ E_{0+}^* (E_{1+} - M_{1+}) + E_{0+}^* (4E_{2+} - 4M_{2-} - M_{2+} - E_{2-}) \cos\theta \right\}.$$  

Above we are omitting the interference terms between $p$- and $d$-wave multipoles for brevity, although they are included in our calculation. They are crucial to understand sensitivity to the $A_{1/2}$ helicity amplitude in our chosen observables. This subtle interference effect of the $p$-wave multipoles is ignored in a recent analysis \[13\] of Tantor et al., as is the complex Lagrangian structure of the spin-$\frac{3}{2}$ vertex in Eqs.(3)-(6).

In the “second” resonance region, around $W \sim 1.3$ GeV, of interest here, the dominant multipole for eta photoproduction is $E_{0+}$, and its primary contribution is from the excitation of the $N^*(1535)$ resonance \[12\]. Both the $E_{0+}$ and $M_{1-}$ multipoles also receive contributions from the spin-$\frac{1}{2}$ sector of the $N^*(1520)$, often referred to as the off-shell sector \[9\] of the spin-$\frac{3}{2}$ resonance. This is controlled by the parameters $X, Y, Z$ introduced earlier in Eqs. (3)-(5). The multipoles $E_{2-}$ and $M_{2+}$, in which $N^*(1520)$ is resonant, are relatively small in the energy region of our interest, but are retained for an important reason. Their effects are enhanced by the interference with the large $E_{0+}$ multipole (Eqs.7-9), in contrast to pion photoproduction where no single multipole stands out.

The differential cross-section $\frac{d\sigma}{d\Omega}$ of the reaction (1), recently determined at the Mainz Microtron \[9\], is very flat...
near the eta photoproduction threshold characteristic of the dominance of the $E_{0+}$ multipole and $N^*(1535)$ excitation. As the photon energy increases, the differential cross-section begins to deviate from near isotropy and shows angular dependence (Figs.1, first column). This has been interpreted as a complicated effect of a combination of nucleon Born terms and the role of the $N^*(1520)$ excitation. However, the best fit of the Mainz data alone misses the sign of the PTA (Figs.1, second column) and cannot reproduce the magnitude of the PPA (Figs.1, third column). It is only a combination of these three data sets, encompassing broad energy range, [4-6] that results in the acceptable fits to all these diverse data, a sample of which is represented by the solid lines. There is also incompatibility between the low energy PTA data and other observables. If we force a fit to the low-energy data, we cannot use that (dashed lines) to describe the higher energy data sets. We should recall that isobar model fits of the low-energy PTA data have been so far unsuccessful.

This brings us to the subject of nodal structure of the observables as fingerprints of resonance contributions. The nodal structure anticipated by Saghai and Tabakin for pure s- and d-wave resonances, follows from a $\sin\theta \cdot \cos\theta$ distribution for the PTA. However, the s-wave interfering with the $p$ and d-wave multipoles, predicted in our effective Lagrangian approach, spoils this simple expectation. The data at higher energies support the latter, with no node appearing in the PTA (Figs.1, second column). Such deviations are indicative of subtle roles of background contributions.

We have to deal with the problem of broad range of parameters for resonances in the PDG compilation. We adopt the following strategy to do our fits. For a particular set of $N^*(1520)$ parameters, we vary properties of $N^*(1535)$, such as mass, width etc., within the permitted PDG 1996 boundaries. We then change the parameter set of $N^*(1520)$ and repeat the procedure. In this way we cover many possible parameter sets of $N^*(1520)$ and $N^*(1535)$. Shown in Table I are the parameter sets for $N^*(1535)$ excitation. However, the best fit of the Mainz and Bonn data, upto 750 MeV. However, the best fit of the Mainz data alone misses the sign of the PTA (Figs.1, second column) and cannot reproduce the magnitude of the PPA (Figs.1, third column). It is only a combination of these three data sets, encompassing broad energy range, [4-6] that results in the acceptable fits to all these diverse data, a sample of which is represented by the solid lines. There is also incompatibility between the low energy PTA data and other observables. If we force a fit to the low-energy data, we cannot use that (dashed lines) to describe the higher energy data sets. We should recall that isobar model fits of the low-energy PTA data have been so far unsuccessful.

We now discuss the significance of the ratio (12) from the point of view of the structure of the nucleon and $N^*(1520)$. It should be zero in the pQCD regime. We are clearly dealing here with non-perturbative physics that is altering the helicity structure dramatically in the $q^2 \to 0$ limit. This helicity structure is very model-dependent. Many topical models of baryon struc-

\begin{align}
A_{3/2}/A_{1/2} &= -2.5 \pm 0.2 \pm 0.4. \tag{12}
\end{align}
ture in the literature attempt to address this. A sample of their predictions is given in Table II. We note that the non-relativistic quark model of Isgur and Koniuk \[8\] yields a value $-5.6$, while Li and Close \[5\], taking into account effects of color hyperfine interaction in the quark transition operators, are estimating its value in between $-2.5$ to $-4.5$. Our phenomenologically extracted value is in excellent agreement with the prediction ($-2.5$) of Bijker et al. \[1\]. Their model deals with a dynamical $U(7)$ symmetry of the nucleon structure that has a oblate top spectrum. For the $N^*$($1520$) excitation at $q^2 \to 0$, we have confirmed the helicity inequality $|A_{1/2}| < |A_{3/2}|$, from the data, in contrast to the inequality $|A_{1/2}| > |A_{3/2}|$ expected at high $q^2$.

TABLE I. The electrostrong parameters as determined for $N^*$($1535$) and $N^*$($1520$) for different sets of resonance position $M_R$, total width $\Gamma$ and $\eta N$ branching ratio. The sets are: $a_1 = 1544, 212, 0.45$; $a_2 = 1535, 185, 0.45$; $b_1 = 1515, 135, 0.0012$; $b_2 = 1530, 135, 0.0012$; $b_3 = 1530, 110, 0.0012$; $b_4 = 1520, 120, 0.0012$.

| Parameter Set | $\chi^2$ per d.f. | $\xi_{1/2}^0$ | $\xi_{1/2}^D$ | $\xi_{3/2}^D$ | $R$ |
|---------------|-----------------|---------------|---------------|---------------|-----|
| $a_1, b_1$    | 1.349           | 2.221         | -0.053        | 0.145         | -2.73 |
|               | ±0.009          | ±0.017        | ±0.056        |               |     |
| $a_1, b_2$    | 1.308           | 2.218         | -0.075        | 0.186         | -2.48 |
|               | ±0.011          | ±0.021        | ±0.046        |               |     |
| $a_1, b_3$    | 1.310           | 2.219         | -0.080        | 0.198         | -2.47 |
|               | ±0.011          | ±0.021        | ±0.043        |               |     |
| $a_1, b_4$    | 1.329           | 2.221         | -0.063        | 0.167         | -2.65 |
|               | ±0.009          | ±0.019        | ±0.048        |               |     |
| $a_2, b_1$    | 1.329           | 2.308         | -0.051        | 0.132         | -2.59 |
|               | ±0.005          | ±0.011        | ±0.033        |               |     |
| $a_2, b_2$    | 1.301           | 2.307         | -0.074        | 0.172         | -2.32 |
|               | ±0.007          | ±0.015        | ±0.030        |               |     |
| $a_2, b_3$    | 1.295           | 2.307         | -0.074        | 0.181         | -2.44 |
|               | ±0.007          | ±0.015        | ±0.031        |               |     |
| $a_2, b_4$    | 1.308           | 2.307         | -0.059        | 0.152         | -2.58 |
|               | ±0.006          | ±0.013        | ±0.034        |               |     |

TABLE II. The ratio $R = \xi_{3/2}^D / \xi_{1/2}^D$ as predicted in various models \[8\] for the $N^*$($1520$) excitation and decay into $\eta N$, and as determined in a model-independent manner from this work.

| Isgur-Koniuk | Capstick | Li-Bijker | Inferred from PDG 96 | This work |
|--------------|----------|-----------|----------------------|-----------|
| $-5.56$      | $-8.93$  | $-2.49$   | $-2.5$               | $-6.9$    | $-2.5$ |
|              |          | to $-4.86$| $\pm 2.6$           | $\pm 0.2 \pm 0.4$ |

In summary, the recent experimental advances in the study of photoproduction of eta mesons in the second resonance region ($W \sim 1.3$ GeV) have immediate theoretical pay-off for the knowledge of electromagnetic amplitudes that excite $N^*$($1520$). Even though this resonance is a relatively minor player in this reaction, a combination of the differential cross-section and polarization data, coming out of the recent experiments at the photon facilities, have allowed us to infer in a nearly model-independent way the value of the ratio $A_{3/2}/A_{1/2}$, which is predicted to be negative in the QCD-inspired models, but is strongly model-dependent. The magnitude of this ratio is selective among these topical models, and is very different from being zero, expected in the pQCD regime. New theoretical work is needed to explore this ratio on the lattice. On the experimental side, electroproduction of pseudoscalar mesons, at facilities like the CEBAF, will throw new light on the $q^2$ developments of these helicity amplitudes and their longitudinal partner.

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