From known to undiscovered resonances

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Abstract. Electromagnetic meson production formalisms are reviewed, with emphasise placed on their ability in search for new baryon resonances *via* $\gamma p \to K^+\Lambda$ and $\gamma p \to \eta p$ processes. The relevant studies, aiming to deepen our insights to hadron spectroscopy, constitute strong tests of the QCD inspired theoretical developements.

I INTRODUCTION

presently, our knowledge on the baryon resonances comes [1,2] mainly from partial wave analysis of the "pionic" processes $\pi N \to \pi N$, ηN, $\gamma N \to \pi N$, and to less extent, from two pion final states.

The advent of new facilities offering high quality electron and photon beams and sophisticated detectors, has stimulated intensive experimental and theoretical study of the mesons photo- and electro-production. One of the exciting topics here is the search for new baryon resonances which do not couple or couple too weakly to the πN channel. Several such resonances have been predicted [3] by different QCD inspired approaches, offering strong test of the underlying concepts.

In this note, we concentrate on the interpretation of pseudoscalar mesons photoproduction recent data [4–8], where manifestations of new resonances were reported [9,10]. The processes under consideration, $\gamma p \to K^+\Lambda$ and $\gamma p \to \eta p$, are basically studied *via* two families of formalisms:

- Effective Lagrangian approach, where the amplitudes are in general expressed as Feynman diagrams at tree level.
- Constituent quark approach based on the broken $SU(6) \otimes O(3)$ symmetry.

Below, we summarize the basis of these formalisms and examin their findings with respect to the reported new resonances.

II THEORETICAL FRAMES

For several decades, effective Lagrangian family approaches have been extensively developped and applied to the electromagnetic production of pseudoscalar mesons.

Baryon	Three and four star resonances	One and two star resonances
N^*	$S_{11}(1535)$, $S_{11}(1650)$,	$S_{11}(2090)$,
	$P_{11}(1440)$, $P_{11}(1710)$, $P_{13}(1720)$,	$P_{11}(2100)$, $P_{13}(1900)$,
	$D_{13}(1520)$, $D_{13}(1700)$, $D_{15}(1675)$,	$D_{13}(2080)$, $D_{15}(2200)$,
	$F_{15}(1680)$,	$F_{15}(2000)$, $F_{17}(1990)$,
	$G_{17}(2190)$, $G_{19}(2250)$,	
	$H_{19}(2220)$,	
Λ^*	$S_{01}(1405)$, $S_{01}(1670)$, $S_{01}(1800)$,	
	$P_{01}(1600)$, $P_{01}(1810)$, $P_{03}(1890)$,	
	$D_{03}(1520)$, $D_{03}(1690)$, $D_{05}(1830)$,	$D_{03}(2325)$,
	$F_{05}(1820)$, $F_{05}(2110)$,	$F_{07}(2020)$,
	$G_{07}(2100)$,	
	$H_{09}(2350)$,	
Σ^*	$S_{11}(1750)$,	$S_{11}(1620)$, $S_{11}(2000)$,
	$P_{11}(1660)$, $P_{11}(1880)$, $P_{13}(1385)$,	$P_{11}(1770)$, $P_{11}(1880)$, $P_{13}(1840)$,
		$P_{13}(2080)$,
	$D_{13}(1670)$, $D_{13}(1940)$, $D_{15}(1775)$,	$D_{13}(1580)$,
	$F_{15}(1915)$, $F_{17}(2030)$.	$F_{15}(2070)$,
		$G_{17}(2100)$.

TABLE 1. Isospin-1/2 baryon resonances [1] with mass $M_{N^*} \leq 2.5$ GeV. Notations are $L_{2I\ 2J}(mass)$ and $L_{I\ 2J}(mass)$ for N^* and Y^*, respectively.

The most studied channel is by far, the single pion photoproduction where, in the investigated kinematic regions, the reaction mechanism is dominated by the $\Delta(1234)$ resonance. Such a feature has also been observed, although not fully understood, in the case of the η meson production, where the $S_{11}(1535)$ resonance plays a dominant role, at least up to $\approx$ 100 MeV above threshold. However, the associated strangeness production channel has not shown any strong preference for a given resonance.

The recent data from high duty cycle accelerators allow a real break through in this field and extend the measured (measurable) domains well above threshold and give acces to polarization observables. Then, the relevant formalisms need to have the ability of incorporating a large number of resonances summarized in Table 1. This requirement becomes crucial in searching for new baryon resonances, on which this note focuses.

In this Section, we concentrate on two of the most commonly used formalisms, namely, tree level diagrammatic effective Lagrangians [9,11–20], and constituent quark approaches [10,21–23]. For other relevant approaches, the reader is refered to Refs. [10,24].

A Meso-baryonic effective Lagrangian approach

In lines with single photoproduction formalisms, the effective Lagrangian approaches have been extended to the KY [9,11–18] and the ηN [20] final states. In this Section, we limit ourseleves to the former channel.

The history of strangeness physics studies *via* electromagnetic probes can be divided into two periods (see, e.g., Refs. [15,24]). The early works started in the late 50's and went on for about 15 years. Then, in the early 80's, several experimental projects restored this dormant field and gave it a promising future, and due to several foreseen facilities with high quality polarized electron and/or photon beams, revived theoretical investigations in this realm. The starting point of these studies is the effective hadronic Lagrangian approach, using diagrammatic techniques, developed in the old days by Thom, Renard and Renard [11]. However, these works led to a confusing situation [15] on the ingredients of the elementary operator. These pioneering attempts were followed by more extensive investigations [12–18] of the elementary reactions: $\gamma p \rightarrow K^+\Lambda$, $K^+\Sigma^\circ$, $K^\circ\Sigma^+$, with real and virtual photons, as well as the crossing symmetry channels [13,16,17] $K^- p \rightarrow \gamma\Lambda$, $\gamma\Sigma^\circ$.

In this note, we wish to comment on the capability of different formalisms in handling the exchanged resonances in the elementary reaction mechanism.

The most widely used effective Lagrangians are based on the tree approximation, allowing the inclusion of a large number of possible exchanged particles in the *s*-, *u*-, and *t*-channels *via* the relevant Feynman diagrams. Within such phenomenological approaches, *a priori* more than 30 exchanged baryonic resonances (Table 1) can intervene. This uncomfortable situation, where no dominante resonances could be identified, is due to our lack of knowledge [1] on the photo-excitation couplings and/or on the branching ratios of these resonances to the relevant KY final states.

This raises a *crucial question*: does a given formalism allow us to introduce in a model, baryon resonances with spin 1/2, 3/2, and 5/2? Capabilities of the most commonly used formalisms which deal with the above question are summarized in Table 2.

One of the main sources of the level of success of the models built within these formalisms, is the inclusion of the *t*-channel resonances. Actually, we know [25] from the duality hypothesis that there is a close relationship between a dynamical

Resonance (spin) → Group [Ref.] ↓	$N^*(1/2)$	$N^*(3/2)$	$N^*(5/2)$	$Y^*(1/2)$	$Y^*(3/2)$	Off-shell treatment
North Carolina [13]	Y			Y		
Ohio - GWU [9,14]	Y	Y		Y		
Saclay - Lyon [16]	Y	Y	Y	Y		
VPI - Lyon - Saclay [17]	Y	Y		Y	Y	Y
Yonsei [18]	Y	Y	Y	Y	Y	

TABLE 2. Capabilities of the most commonly used formalisms for the process $\gamma p \rightarrow K^+\Lambda$ in handling nucleonic resonances with spin 1/2, 3/2, and 5/2, and hyperonic resonances with spin 1/2 and 3/2. All the models issued from these formalisms include, besides the extended Born terms, the $K^*(892)$ and $K1(1270)$ exchanges in the *t*-channel.

model's content with respect to the included baryon resonances and the corresponding strength of the t-channel exchanges needed to fit the data. However, this artifact does not provide fine enough insights into the reaction mechanism: in a given model, we cannot say which baryon resonances, absent in the model, are mimiked by the t-channel contributions. However, within the formalisms discussed in this Section, serious technical difficulties prevent us from introducing all the known baryon resonances and hence to discard t-channel contributions.

A major problems in the formalisms handling baryonic resonances with spin higher than 1/2 is related to the adopted propagators. As shown by the RPI group [19], the most commonly used propagator [14,16] for spin 3/2 nucleonic resonances has no inverse. Moreover, this undesirable situation prevents those formalisms from introducing spin 3/2 hyperonic resonances, which otherwise would lead to an unwanted singularity in the u-channel. To overcome this serious shortcoming, the RPI group, investigating the pion and η photoproduction reactions, has applied [19] the Rarita-Schwinger approach [26]. Along the same lines, the authors of Ref. [17] have produced a formalism allowing a proper treatment of *both* nucleonic and hyperonic spin 3/2 resonances. For recent discussions on various aspects of this topic see, e.g. Refs [17,19,27,28].

In Sec. III.A, the results of the formalism discussed above, will be compared to the $\gamma p \to K^+\Lambda$ data.

B Constituent quark effective Lagrangian approach

The starting point of the meson electromagnetic production in the chiral quark model is the low energy QCD Lagrangian [29]. The baryon resonances in the s- and u-channels are treated as three quark systems. The transition matrix elements based on the low energy QCD Lagrangian include the s-, u-, and t-channel contributions $\mathcal{M}_{if} = \mathcal{M}_s + \mathcal{M}_u + \mathcal{M}_t$. The contributions from the s-channel resonances can be written as

$$\mathcal{M}_{N^*} = \frac{2M_{N^*}}{s - M_{N^*}(M_{N^*} - i\Gamma(q))} e^{-\frac{k^2+q^2}{6\alpha_{ho}^2}} \mathcal{A}_{N^*}, \tag{1}$$

where k and q represent the momenta of the incoming photon and the outgoing meson respectively, $\sqrt{s} \equiv W$ is the total c.m. energy of the system, $e^{-(k^2+q^2)/6\alpha_{ho}^2}$ is a form factor in the harmonic oscillator basis with the parameter α_{ho}^2 related to the harmonic oscillator strength in the wave-function, and M_{N^*} and $\Gamma(q)$ are the mass and the total width of the resonance, respectively. The amplitudes $\mathcal{A}_{N^*}$ are split into two parts [21]: the contribution from each resonance below 2 GeV, the transition amplitudes of which have been translated into the standard CGLN amplitudes in the harmonic oscillator basis, and the contributions from the resonances above 2 GeV treated as degenerate, since little experimental information is available on those resonances.

The u-channel contributions are divided into the nucleon Born term and the contributions from the excited resonances. The matrix elements for the nucleon Born term is derived explicitly, while the contributions from the excited resonances above 2 GeV for a given parity are assumed to be degenerate so that their contributions could be written in a compact form.

The t-channel contribution contains two parts: *i)* charged meson exchanges which are proportional to the charge of outgoing mesons and thus do not contribute to the process $\gamma N \to \eta N$; *ii)* ρ- and ω-exchange in the η production which are excluded here due to the duality hypotheses; as discussed in Ref. [10].

Within the exact $SU(6) \otimes O(3)$ symmetry the $S_{11}(1650)$ and $D_{13}(1700)$ do not contribute to the investigated reaction mechanism. However, the breaking of this symmetry leads to the configuration mixings. Here, the most relevant configuration mixings are [10] those of the two S_{11} and the two D_{13} states around 1.5 to 1.7 GeV. The configuration mixings, generated by the gluon exchange interactions in the quark model [30], can be expressed in terms of the mixing angles, Θ_S and Θ_D, between the two $SU(6) \otimes O(3)$ states $|N(^2P_M)>$ and $|N(^4P_M)>$, with the total quark spin 1/2 and 3/2. Results of this approach will be compared to the data for $K^+\Lambda$ and ηp channels in Sections III.A and III.B, respectively.

III EVIDENCE FOR NEW RESONANCES?

A Associated strangeness production

Recent SAPHIR data [4] for the $\gamma p \to K^+\Lambda$ process has been claimed [9] to provide *evidence* for a missing D_{13} resonance [31]. In their work based on a meso-baryonic effective Lagrangian approach (see Sec. II.A), Mart and Bennhold (MB) produce a model which contains contributions from;

- Extended Born terms.
- Two kaonic resonances in the t-channel: $K^*(892)$ and $K1(1270)$.
- Three established nucleonic resonances in the s-channel: $S_{11}(1650)$, $P_{11}(1710)$, and $P_{13}(1720)$; hereafter referred to as $N4$, $N6$, and $N7$, respectively. Notice that (Table 1) the two first resonances have spin-1/2, while the third one is a *spin-3/2* resonance. The propagators are in line with those in Ref. [14] and *do not* embody off-shell treatments.
- One unknown (or missing) *spin-3/2* nucleonic resonance, that the authors determine as $D_{13}(1895)$.

It is to be noted that this model has no hyperonic resonances.

Figure 1 shows the total cross section data and the MB complete model (dash-dotted curve). MB report [9] also results with a model containing all the above ingredients, except the missing resonance. The main feature of this latter model is that it does not produce any structure around W=1.9 GeV, as required by the (fitted) data. Using the Saclay-Lyon model [16], we [24] have fitted the same data base (including differential and total cross-sections from SAPHIR, old recoil Λ asymmetry [32], and recent JLab electroproduction data [33]) as MB. Limiting the reaction mechanism to the above ingredients without the missing D_{13} resonance, we obtain the same features as MB. Our fit for the [N4, N6, N7] set is shown in Fig. 1 (dashed curve) and decreases monotonically beyond a maximum around W=1.72 GeV. As a next step, and for the reason explained in Section II.A, we include the off-shell effect treatments in line with Ref [17]. We then get the dotted curve which shows a significant enhancement in the cross section above 1.85 GeV. By introducing two hyperonic resonances $P_{01}(1810)$ and $P_{03}(1890)$ (hereafter called $L5$ and $L8$, respectively), the data are well reproduced (full curve). This set of resonances [N4, N6, N7, L5, L8] reproduces reasonably also the other fitted data. Our results therefore show that there is *no need* for a missing resonance.

The above considerations can not be taken as an attempt to produce a new model, but just as an *illustration* as how cautious we have to be in using the existing formalisms when searching for new resonances. A more reliable approach in this respect, should allow us to embody all known resonances.

Such an opportunity is offered to us by the constituent quark formalims presented in Section II.B. We [23] have included all known nucleon and hyperon resonances given in Table 1, and have fitted the photoproduction data base. The result is given in Fig. 1 (heavy dashed curve). The agreement between this latter curve and the data endorses our conclusions that the SAPHIR data does not show any manifestations of a new resonance.

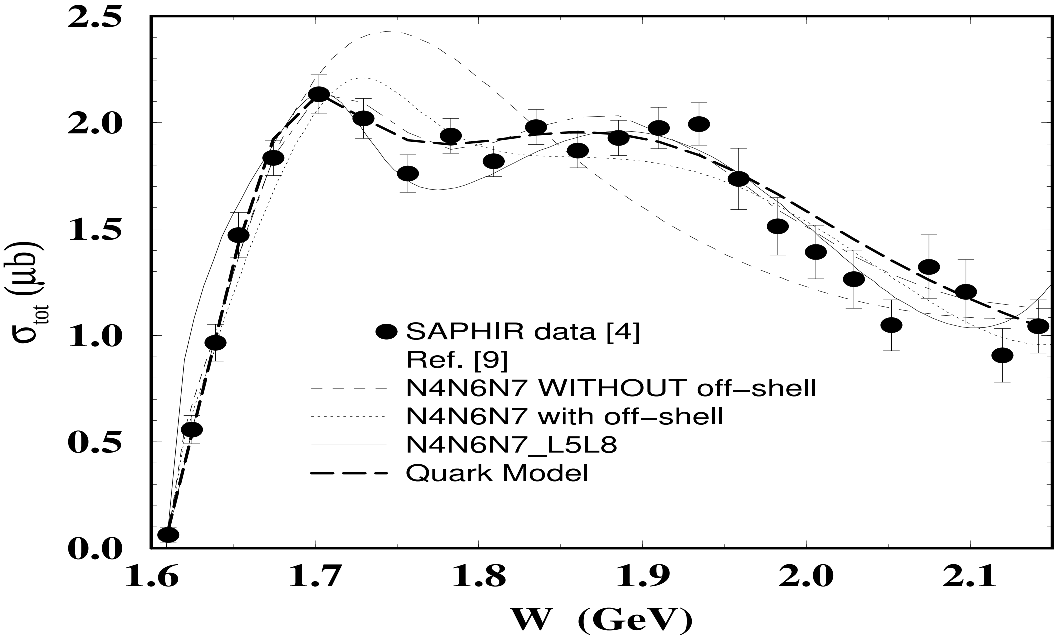

FIGURE 1. Total cross section for the process $\gamma p \rightarrow K^+\Lambda$ as a function of total center-of-mass energy.

B η-meson production

Using a constituent quark model (Section II.B), we [10] have fitted the following sets of the η-photoproduction data: differential cross-sections from MAMI/Mainz [5] and Graal [8], as well as the polarized beam asymmetry from Graal [7]. Then we have predicted [10] the total cross-section and the polarized target asymmetry. This latter observable has been measured at ELSA [6].

In Fig. 2, we show comparison for the total cross-section, for the models I and II. Both models include all 3 and 4 star known nucleon resonances (Table 1). They also satisfy the configuration mixing requirements and for both models, the extracted mixing angles are in agreement with the Isgur-Karl [30] predictions.

The model I reproduces fairly well the total cross-section data up to $W \approx 1.61$ GeV. Between this latter energy and ≈ 1.68 GeV, the model overestimates the data, and above 1.68 GeV, the predictions underestimate the experimental results, missing the total cross-section increase.

In summary, results of the model I show clearly that an approach containing a correct treatment of the Born terms and including *all known resonances* in the s- and u-channels *does not* lead to an acceptable model, even within broken $SU(6) \otimes O(3)$ symmetry scheme. To go further, one possible scenario is to investigate manifestations of yet undiscovered resonances. As already mentioned, rather large number of such resonances has been predicted by several authors. To find out which ones

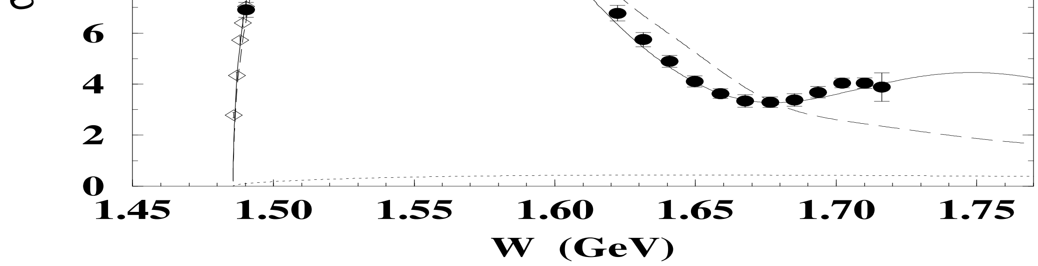

FIGURE 2. Total cross section for the reaction $\gamma p \to \eta p$ as a function of total center-of-mass energy. The curves come from the models I (dashed), II (full). The dotted curve shows the background terms contribution in the model II.

could be considered as relevant candidates, we examined the available data.

The differential cross-sections [10,34], show clearly that this mismatch is due to the forward angle peaking of the differential cross-section for $W \geq 1.68$ GeV ($E_{\gamma}^{lab} \geq$ 1. GeV). Such a behaviour might likely arise from missing strength in the S-waves. This latter conclusion is endorsed by the role played by the E_0^+ in the multipole structure of the differential cross-section and the single polarization observables. If there is indeed an additional S-wave resonance in this mass region, its dependence on incoming photon and outgoing meson momenta would be qualitatively similar to that of the $S_{11}(1535)$, even though the form factor might be very different. Thus, for this new resonance, we use the same CGLN amplitude expressions as for the $S_{11}(1535)$. We have hence introduced [1] a third S_{11} resonance and refitted the same data base as for the model I, leaving it's mass and width as free parameters. The results of this model, depicted in Fig. 1 (full curve), reproduce nicely the data. This is also the case [10] for the polarized beam and polarized target asymmetries. For this latter observable, our predictions yield a good agreement with the data.

For the new S_{11} resonance, we find M=1.729 GeV and Γ=183 MeV. These values are amazingly close to those of a predicted [35] third S_{11} resonance, with M=1.712 GeV and Γ_T=184 MeV.

IV SUMMARY AND CONCLUDING REMARKS

In this note we concentrated on the search for new resonances *via* the two processes $\gamma p \to K^+\Lambda$, ηp for which recent data have become available.

The effective Lagrangian approaches, using Feynman diagrams at tree level, applied to the above channels, allow to study some specific aspects of the reaction mechanism. However, they are not suitable in looking for new resonances. The reason for this shortcoming is that they do not allow the inclusion of *all* relevant known resonances. Although the introduction of spin-1/2 resonances is straightforward, higher spin resonances are more complicated to be handlded. The main difficulty comes from the incorporation of the so called *off-shell effects*, inherent to the fermions with spin $\geq 3/2$. Presently, these effects can be embodied for spin-3/2 resonances, but no conclusive attempt has been made for higher spins. Another limitation of these approaches is due to the number of free parameters: one for each spin-1/2, two for each higher spin, plus 3 off-shell parameters per resonance. In other words, even if we were able to treat all higher spin resonances correctly, the very large number of parameters would not allow to reach any clear conclsions on the possible manifestations of new resonances. Notice that such resonances are expected above the first resonance region, where higher spin resonances are expected to play significant roles.

The advantage of the quark model for the meson photoproduction is the ability to introduce all known resonances. Moreover, the number of adjustable parameters, one per resonance in the broken $SU(6)\otimes O(3)$ limit, stays much smaller than in the case of the above formalism. Contrary to the former approache, the quark model adjustable parameters measure the extent to which the $SU(6) \otimes O(3)$ symmetry is broken. Hence, they should stay rather close to their $SU(6) \otimes O(3)$ symmetry values, while in the case of effective Lagrangians, apart for a few exceptions, there are no constraints on the range of the fitted parameters. Besides, the constituent quark models allow us to relate the data directly to the internal structure of the baryon resonances.

The main conclusion here is therefore: *the appropriate framework in search for new baryonic resonances is constituent quark approaches.*

The above conclusion was illustrated in this note by two examples and the findings are:

- Recent $\gamma p \to K^+\Lambda$ SAPHIR data can be understood by taking into account the known resonances within an effective hadronic Lagrangian approach embodying off-shell effects for spin-3/2 baryon resonances, as well as within a constituent quark model. There is hence no need for introducing unkown resonances.
- Investigation of the recent $\gamma p \to \eta p$ Graal data within a chiral constituent quark approach based on the broken $SU(6) \otimes O(3)$ symmetry, shows clear need for a new S_{11} resonance, with mass $M \approx 1.730$ GeV and total width $\Gamma \approx$180 MeV.

To gain insights to the nature of this resonance, an extension of the η electroproduction studies above the first resonance region is in progress [36]. Investigation of vector meson electromagnetic production within constituent quark models [37,38] appears also very promissing in baryon spectroscopy.

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