

Baryon resonance analysis from SAID^{*}

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Abstract We discuss the analysis of data from πN elastic scattering and single pion photo- and electroproduction. The main focus is a study of low-lying non-strange baryon resonances. Here we concentrate on some difficulties associated with resonance identification, in particular the Roper and higher P_{11} states.

Key words non-strange baryons, N(1440), pion-nucleon elastic scattering, pion photo- and electro-production

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1 Introduction

Many of the SAID fits to scattering data have been motivated by ongoing studies of the N^* properties^[1]. Most of these (for instance, EBAC^[2], Giessen^[3], DMT^[4], Jülich^[5]) have used, as input, amplitudes extracted from elastic πN scattering data^[6, 7]. Our pion photoproduction multipoles are also determined using a K -matrix formalism based upon πN partial-wave amplitudes^[8–10]. Further, the pion-electroproduction analysis is anchored to our $Q^2 = 0$ photoproduction results, with additional factors intended to account for the Q^2 variation^[11].

One of the most convincing ways to study the spectroscopy of non-strange baryons is through πN partial-wave analysis (PWA). The main sources of the Review of Particle Physics (RPP) N^* Listings^[1] are the PWA of the KH, CMB, and GW/VPI groups. The analysis of πN scattering data remains crucial in this effort. Double-polarization quantities (R and A) measured long after the KH and CMB analyses were completed have found discrepancies in these earlier fits, which weakens claims for the existence and properties of some of the weaker (mainly isospin 3/2) resonances.

In the GW DAC πN PWA, we determine πN amplitudes by the fitting πN elastic data (up to $W = 2.50$ GeV) and $\pi^- p \rightarrow \eta n$ data (up to $W = 1.63$ GeV). Resonances are then found through a search for poles in the complex energy plane. We consider mainly

poles which are not far away from the physical axis. It is important to emphasize that these resonances are not put in by hand, contrary to the Breit-Wigner (BW) parametrization. The poles arise, in a sense, dynamically as a result of the enforced (quasi-) two-body unitarity cuts and the fit to the observable on the real energy axis. We have, however, also given the results of a BW parametrization, mapping $\chi^2[W_R, \Gamma]$ while searching all other partial-wave parameters by fitting data over a relatively narrow energy range, say 100–200 MeV. Some subjectivity in the BW study is involved, such as: (i) energy binning, (ii) the strength of constraints (such as dispersion relations), and (iii) the choice of partial waves to be searched. We should stress that the standard PWA reveals resonances with widths of order 100 MeV, but not too wide ($\Gamma > 500$ MeV) or possessing too small a branching ratio ($BR < 4\%$), tending (by construction) to miss narrow resonances with $\Gamma < 30$ MeV. The partial waves of solution KA84^[12] and the single-energy solutions (SES) associated with our SP06 results agree reasonably well over the full energy range of the SP06 (Figs. 4–7 from Ref. [6]). However, this does not lead to agreement on the resonance content. For instance, our study^[6] does not support several N^* and Δ^* reported by PDG^[1]. It is important here to remember that during last 25 years, the πN database has increased by a factor of 3–4, and these data were not available to the KH and CMB groups.

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2 πN features

2.1 Minimization and normalization factor

As in previous analyses, we have used the systematic uncertainty as an overall normalization factor for angular distributions. Renormalization freedom significantly improves our best-fit results, as shown in

Table 1. Comparison of χ^2/data values (Norm/Unnorm) for normalized (Norm) and unnormalized (Unnorm) data used in the SP06^[6] and FA02^[7] solutions, Karlsruhe KA84^[12], EBAC^[2], Giessen^[3], and DMT^[4]. Values for SP06 (FA02) correspond to a 2.46 (2.26) GeV energy limit for W in CM. KA84 is evaluated up to 2.9 GeV, EBAC up to 1.91 GeV, Giessen up to 2 GeV, and DMT up to 2.2 GeV.

reaction	SP06	FA02	KA84	EBAC	Giessen	DMT
	χ^2/data	χ^2/data	χ^2/data	χ^2/data	χ^2/data	χ^2/data
$\pi^+ p \rightarrow \pi^+ p$	2.0/6.1	2.1/8.8	5.0/24.9	13.1/23.7	10.5/17.7	15.4/37.4
$\pi^- p \rightarrow \pi^- p$	1.9/6.2	2.0/6.6	9.1/51.9	4.9/16.0	12.1/34.1	9.0/23.0
$\pi^- p \rightarrow \pi^0 n$	2.0/4.0	1.9/5.9	4.4/8.8	3.5/6.3	6.3/15.2	6.5/16.7
$\pi^- p \rightarrow \eta n$	2.5/9.6	2.5/10.5				

2.2 Roper

Discovered more than 40 years ago^[13], this resonance state has remained controversial for many years. The prominent $N(1440)P_{11}$ resonance is clearly evident in both KH and GW/VPI analyses (Figs. 4–7 from Ref. [6]), but occurs very near the $\pi\Delta$, ηN , and ρN thresholds (Fig. 8 from Ref. [7]), making a BW fit questionable. The $N(1440)$ is unique in that its behavior on the real energy axis is influenced by poles on different Riemann sheets (with respect to the $\pi\Delta$ -cut) as was first reported by Arndt et al.^[14]. Due to the nearby $\pi\Delta$ threshold, both P_{11} poles are not far from physical region (Fig. 1). There is a small shift between pole positions on the two sheets, due to a non-zero jump at the $\pi\Delta$ -cut. Our conclusion is that a simple BW parametrization cannot account for such a complicated structure. This point was also emphasized by Höhler^[1]. Recent studies by the Jülich^[5] and EBAC^[15] groups have confirmed the two pole determination. An earlier study by Cutkosky and Wang came to a similar conclusion^[16].

Following the first indications from PWA studies, evidence^[17] for the Roper was found through the analysis of hydrogen bubble chamber events. More recent evidence for a direct measurement of the $N(1440)$ has been found using electromagnetic interactions (at BES in $e^+e^- \rightarrow J/\psi \rightarrow p\pi^- \bar{n} + n\pi^+ \bar{p}$ ^[18] and at JLab in $ep \rightarrow e'X$ ^[19]). Hadronic processes (at SATURNE II in $\alpha p \rightarrow \alpha'X$ ^[20] and at Uppsala in $pp \rightarrow np\pi^+$ ^[21]) have also studied. Some of the peaks found have positions different from the BW interpretation of πN

Table 1 (we use the same methodology in all of our PWAs). This renormalization procedure was also applied to the other non-SAID solutions. Here, however, only the normalization constants were searched to minimize χ^2 (no adjustment of the partial waves was possible). Clearly, this procedure can significantly improve the overall χ^2 attributed to a fit (we cannot ignore this experimental input), and has been applied in calculating the χ^2 values of Table 1.

elastic scattering^[1, 6] with “masses” closer to the real part of the pole position^[6, 7]. These differences could reflect the complicated structure described above.

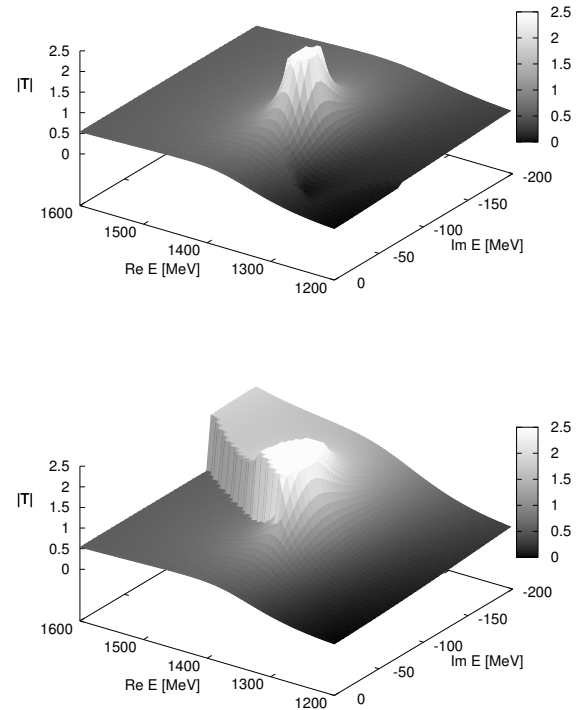


Fig. 1. Two poles for $\pi N P_{11}$. Top: the $\pi\Delta$ cut can be seen in the foreground and runs from larger to smaller values of the real part of the energy. Bottom: the $\pi\Delta$ cut is clearly visible running from smaller to larger values of the real part of the energy.

Overall, most of analyses of $N(1440)$ are based on its BW parametrization, which implicitly assumes that the resonance is related to an isolated pole. However, given the complicated structure found in our PWA, the BW description may be only an effective parametrization, which could be different in different processes. Some inelastic data indirectly support this point, giving $N(1440)$ BW masses and widths significantly different from the PDG BW values^[1]. This may also cast some doubt on recent Q^2 evaluation results^[22, 23], since the Q^2 -dependences for contributions of different singularities may be different. This problem can be studied in future measurements with JLab CLAS12.

2.3 P_{11} beyond 1500 MeV

Beyond the Roper resonance, the P_{11} partial wave wraps around the center of the Argand diagram (Fig. 2) and the total elastic cross section is half the total cross section (Fig. 3). As a result, small changes in the amplitude can produce large changes in the phase, though these changes have little influence on the fit to data. For πN elastic scattering, we conclude that there is little sensitivity to resonances in P_{11} above 1500 MeV except possible states with small Γ_{el} ^[24].

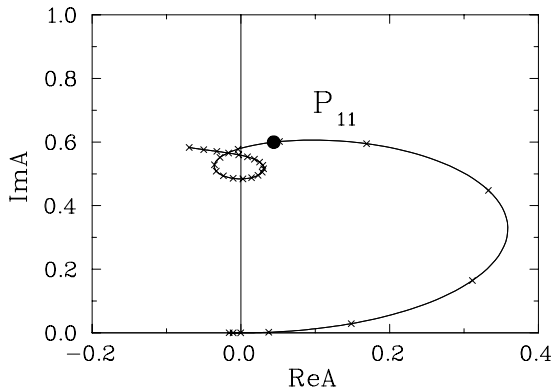


Fig. 2. Argand plot for the P_{11} partial-wave amplitude from threshold (1080 MeV) to $W = 2500$ MeV. Crosses indicate 50 MeV steps in W . The solid circle corresponds to the SP06 BW W_R .

One may speculate about the existence of a very narrow P_{11} state which, as mentioned above, would not be clearly evident in a standard PWA. Such a state was originally motivated by investigations aiming to explain how a very narrow (less than 1 MeV) pentaquark state could exist. Here we can summarize our knowledge of one such “narrow” candidate, $N(1680)P_{11}$:

(i) Using a modified PWA^[24], designed to search for slots where a very narrow state would not destroy

the existing fit to pion-nucleon elastic scattering data, a candidate energy was found at 1680 MeV with a $\Gamma_{\pi N} < 0.5$ MeV.

(ii) There are several independent suggestions for the $N(1680)$ ^[25–27],

(iii) Its width is much less than any non-strange N^* ^[24–27],

(iv) The Chiral-soliton approach gives support for $N(1680)$ production in both γp and γn ^[28],

(v) The GRAAL $\gamma n \rightarrow \eta n$ cross section measurements allow one to determine the radiative width of $N(1680)$ and transition magnetic momentum^[29] which is much smaller than for the Δ case.

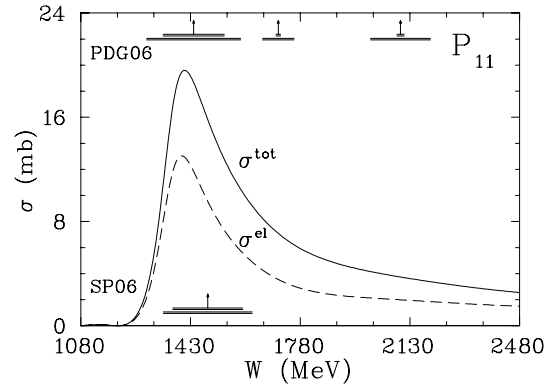


Fig. 3. P_{11} contribution to total and total elastic cross sections for SP06. Vertical arrows indicate resonance W_R values and horizontal bars show full Γ and partial $\Gamma_{\pi N}$ widths. The lower BW resonance symbols are associated with the SP06 values; upper symbols give PDG values, which include higher mass states.

2.4 $\pi^- p \rightarrow \eta n$ database puzzle

Most measurements of the $\pi^- p \rightarrow \eta n$ reaction cross section are rather old and sometimes conflicting (Fig. 4). There are few cross section (106 data) measurements above 800 MeV and no polarized measurements below 1040 MeV^[30]. A detailed analysis of the older data can be found in the review by Clajus and Nefkens^[31]. Most NIMROD data do not satisfy a consistency requirement [systematics are not under control, momentum uncertainties up to 50 — 100 MeV/ c , and so on]. For this reason, we are not able to use these data in our $\pi^- p$ elastic, $\pi^- p \rightarrow \pi^0 n$, and $\pi^- p \rightarrow \eta n$ analyses of scattering data. In particular, the data above 800 MeV does not permit a model-independent analysis of $\pi^- p \rightarrow \eta n$.

The existing data types and energy limits severely restrict any attempt to determine resonance parameters above the first S_{11} resonance.

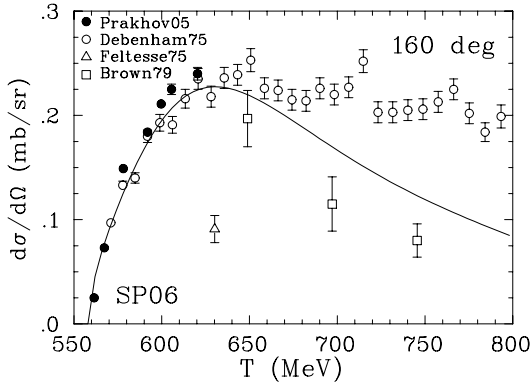


Fig. 4. Fixed angle excitation functions for $\pi^- p \rightarrow \eta n$. We are not able to use data shown by open symbols in our analysis.

3 Pion photo- and electroproduction

In fitting the electroproduction database, we extrapolate from the relatively well determined $Q^2 = 0$ point. The photoproduction multipoles can be parametrized using a form containing the Born terms (no free parameters) and phenomenological pieces maintaining the correct threshold behavior and Watson's theorem below the two-pion production threshold. The πN T matrix connects each multipole to structure found in the elastic scattering analysis. The parametrization above two-pion production is based on a unitary K -matrix approach, which no strong constraints on the energy dependence apart from correct threshold properties.

Overall, the difference between MAID and GW/VPI amplitudes tends to be small but resonance content may be essentially different (Figs. 7 and 8 from^[10]). One reason for differences is database dependent. MAID07^[22] did not use recent CLAS $\pi^0 p$ ^[9] and $\pi^+ n$ ^[10] with LEPS $\pi^0 p$ ^[32] backward measurements. Other differences are tied to different assumptions regarding the inclusion of resonance and background contributions. Some rather large differences are evident in those wave connected to the pion-nucleon S_{11} and D_{13} partial waves.

There are several issues in pion photoproduction above the $\Delta(1232)$ which require resolution. We consider them in the remainder of this section.

3.1 Forward $\pi^0 p$ photoproduction

For incident photon energies up to 1.3 GeV, the $\pi^0 p$ data obtained the CLAS Collaboration^[9] are for the most part in very good agreement with previous measurements. At higher energies, a disagreement between the CB-ELSA^[33] measurements and

the CLAS appears especially at forward angles (Fig. 8 from Ref. [9]). The overall systematic uncertainty for the CB-ELSA measurements is stated to be 5% below 1300 MeV and 15% above that energy. This compares with the roughly 5% systematic uncertainty obtained at JLab.

Moreover, the CLAS $\pi^0 p$ measurements and SAID fit do not confirm the existence of weak states reported by the BoGa group in a fit to the CB-ELSA data^[34].

Given the smooth behavior exhibited by the excitation functions in Figs. 9 and 10 from Ref.[9], the CLAS cross sections provide no hint of “missing” resonance structure between 2 and 3 GeV. The SAID fits implicitly contain only those resonances found in the corresponding SAID analysis of elastic πN scattering data. No change in the form of the SAID photoproduction fit was found to be necessary. In contrast, the CB-ELSA fit required many additional resonance contributions, some of which are 1- and 2-star rated PDG states, as well as a new N(2070) resonance. One possible explanation is apparent in Fig. 10 from^[9], which shows the CLAS data to be somewhat smoother than the CB-ELSA excitation functions. Model-dependence in the separation of resonance and background contributions is also a critical factor. This uncertainty may be reduced through measurements of further (polarized) data.

Clearly, additional measurements at forward angles are needed to determine whether the rapid increase suggested by the most forward CB-ELSA data is correct, or whether the behavior suggested by the most recent fits properly describes the cross section at forward angles. That is critical because the forward measurements are sensitivity to highest N^* s (most of these are inelastic).

3.2 $\pi^- p$ Photoproduction

Complementary measurements of π^\pm photoproduction are required for an isospin decomposition of the multipoles. There are no prior comprehensive tagged $\pi^- p$ measurements. Final-state-interactions (FSI) play a critical role in a state-of-the-art analysis of the $\gamma n \rightarrow \pi^- p$ data. A preliminary study suggests FSI (Fermi motion included) varies between 15 and 40% for the CLAS energy range ($E_\gamma = 1050 - 3500$ MeV) and depends on the energy and scattering angle. There are some previous measurements coming from hadronic facilities but few data are available to accomplish a reliable PWA and determine neutron couplings. A JLab analysis addressed to these data is coming from the $\gamma d \rightarrow \pi^- pp$ experiment (g10 run

period) (in progress). The difference between previous and CLAS measurements may result in significant changes for the neutron couplings.

3.3 Pion electroproduction

Ongoing fits incorporate all available electroproduction data, with modifications to our fitting procedure implemented as necessary (Table 2). We note that the CLAS Collaboration produced 85% of the world pion electroproduction data, much of which was focused on the mapping of the properties of the $\Delta(1232)$ resonance. Useful comparisons will require those involved in this effort to make available all amplitudes obtained in any new determination of R_{EM} and R_{SM} for the $\Delta(1232)$ which may be compared with LQCD calculations^[35].

Table 2. GW N* program.

reaction	data	χ^2
$\gamma^*p \rightarrow \pi^0p$	55,766	81,284
$\gamma^*p \rightarrow \pi^+n$	51,312	80,004
redundant	14,772	17,375
total	124,453	178,663
$\gamma p \rightarrow \pi N$	24,888	50,684
all photo	159,341	229,317
$\pi N \rightarrow \pi N$	31,876	57,255
all πN	191,217	286,572

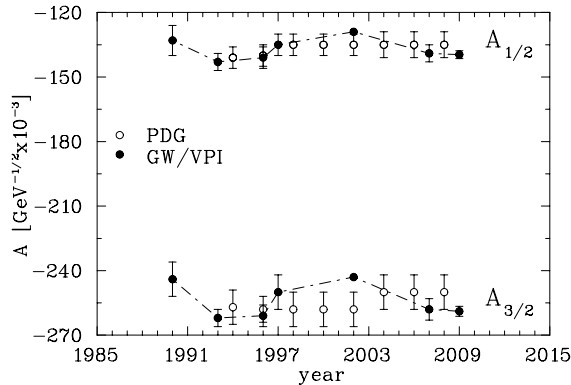


Fig. 5. Time variation of the $A_{1/2}$ and $A_{3/2}$ proton couplings for the $\Delta(1232)$.

Of all resonances, one might assume that the $\Delta(1232)$ properties are known to great precision. Unfortunately, this is not really true (Fig. 5). The PDG average values look stable while our determination depends on the database. The first jump (1990—1993) is associated with the π^0p LEGS activity, the 2nd jump (1993—1996) is the product of the MAMI-B for π^0p and Bonn π^+n activity, the 3rd jump (1996—1997) depends again from MAMI-B for π^0p and Bonn π^+n activity, then 4th jump (1997—2003)

is the result of MAMI-B for π^0p and Bonn with MAMI-B π^+n activity, and finally, the 5th jump (2003—2007) depends from MAMI-B for both π^0p and π^+n .

A major pion electroproduction database problem is that most data are from unpolarized measurements. There are no π^0n data and very few π^-p data (no polarized measurements). This does not allow a rigorous neutron coupling evaluation vs. Q^2 . The Q^2 distribution of available data is shown in Fig. 6.

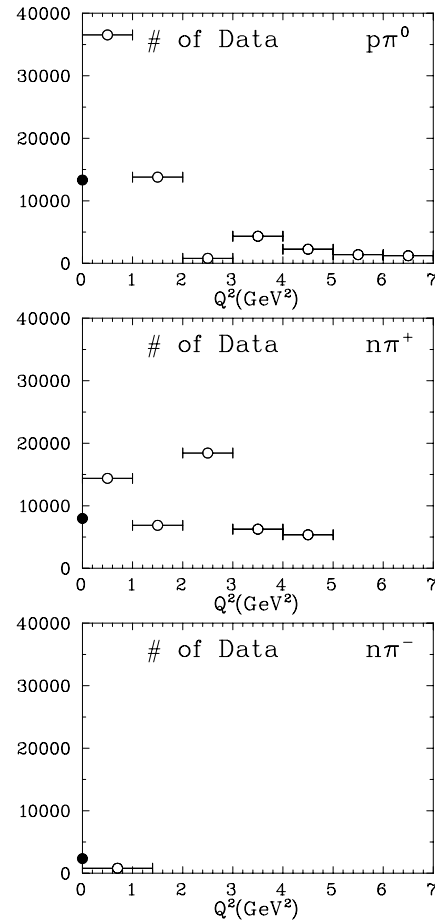


Fig. 6. Q^2 distribution of pion electroproduction data which are now available.

4 Summary and prospects

Let us, in the interest of clarity, summarize where the analysis of the single meson productions reactions stands.

- i) πN analysis is crucial for the N* program,
- ii) Extended πN elastic and pion production analyses are done up to $W = 2500$ MeV,
- iii) $\pi N \rightarrow \eta N$ and eta photoproduction analyses are done up to $W = 1640$ MeV.

Looking forward, our efforts will be focused on the following important issues.

i) Production measurements on the “neutron” target are necessary to determine neutron couplings at $Q^2 = 0$,

ii) Future improvement will be possible with future measurements of spin observables at JLab, MAMI-C, LEPS, LNS, and CB-ELSA,

iii) Complete experiments make possible a direct reconstruction of helicity amplitudes for pion and eta photoproduction.

Finally, issues which will receive further attention are as follows.

i) Q^2 evaluation of resonance couplings up to very large Q^2 ,

ii) The critical question is can we reach an asymptotic regime as pQCD predicted?

iii) Neutron electroproduction measurements are necessary to determine neutron couplings at $Q^2 > 0$.

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