NUCLEON RESONANCE PROPERTIES IN MULTICHANNEL APPROACHES

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Nucleon resonance properties are compared in different multichannel analyses. The approaches incorporate unitarity and as a minimum include the πN, $\pi\pi N$, ηN and γN asymptotic states. They differ in their descriptions of the background, resonance parameterizations and degree of incorporating theoretical constraints and symmetries, such as analyticity, gauge invariance and chiral symmetry. We find that in most cases the properties of the first resonance in each partial wave are in fair agreement with each other. For each second resonance in a given partial wave the extracted masses may be similar but its properties vary widely. Any evidence for a third resonance in a particular partial wave is tenuous.

1 Introduction

In contrast to atomic physics the excited states of the nucleon cannot simply be inferred from cleanly separated spectral lines. Rather, a "spectral analysis" in nucleon resonance (N^*) physics is complicated by the fact that the resonances are broadly overlapping states which decay into a multitude of final states involving mesons and baryons. For this purpose, a number of laboratories like MAMI, ELSA, BATES, GRAAL and TJNAF have developed extensive experimental programs to address the issue of N^* physics, and have begun to deliver new experimental data with unprecedented accuracy. In order to provide a link between the new and improved data on one side and the results from lattice QCD, QCD sum rules and QCD-inspired quark models on the other side, dynamical descriptions using hadronic degrees of freedom are required that can analyze the data in the various asymptotic reaction channels, like $\gamma N, \pi N, \pi\Delta, \rho N, \eta N, K\Lambda$, and others.

2 Coupled-channels Analyses

In order to provide a consistent and complete picture of an individual nucleon resonance, the various possible production and decay channels must be treated in a multichannel framework that permits separating resonance from background contributions. In this paper, we compare the results of three such analyses from the GW-Giessen collaboration[1,2], the Pitt-ANL collaboration[3] and the Kent State University group[4]. To our knowledge, these are the only presently ongoing multichannel studies that include as a minimum the πN, $\pi\pi N$, ηN and γN asymptotic states. All three studies incorporate unitarity and allow the separation of background from resonance contributions. Although model dependent and subject to conceptual uncertainties, these resonance couplings can be compared to results from quark models, QCD sum rule calculations and QCD lattice results. We emphasize that the comparison is not rigorous at this time since the fits were not performed with the identical database. The conclusions drawn in this paper should therefore be regarded as preliminary.

2.1 The GW-Giessen model

The GW-Giessen approach solves a Bethe-Salpeter equation in the K-matrix Born approximation. The driving terms consist of s-, u- and t-channel Feynman diagrams defined through effective Lagrangians. The K-matrix approximation allows the resonance widths to be generated dynamically, while the principal-value part of the meson-baryon propagator is neglected, thus analyticity is not maintained. Because the full Lorentz and Dirac spin structure of the resonance vertices and propagators is included, the model is presently limited to resonances with spin 1/2 and 3/2; the extension to spin 5/2 states is in progress. The field-theoretical basis of the model allows straightforward implementation of gauge invariance and chiral symmetry constraints. Its asymptotic states are $\gamma N, \pi N, \pi\pi N, \eta N, K\Lambda, K\Sigma$ and $\eta' N$; the $\pi\pi N$ channel is approximated by a fictitious isovector, scalar meson with the mass of two pions. Because the background is given by a small number of physical diagrams all partial waves must be fitted simultaneously. This very feature limits the range of applicability to $W = 2.0$ GeV at the present time.

2.2 The Pitt-ANL model

The Pitt-ANL fitting results come from an updated and extended version of the CMB model[5]. The basic model provides a unitary, analytic representation of s-channel resonances that couple to an arbitrary number of asymptotic states; t-channel diagrams must be added by hand. In the Pitt-ANL implementation, photoproduction of pions and etas is included with both resonant and Born diagrams, though gauge invariance is not assured. The main strength of the model is the good description of the features of the analytic plane, particularly the inelastic threshold openings. Each resonance is a bare pole which becomes a pole in the complex plane through inelastic processes (coupling to open channels). Its asymptotic states are $\gamma N, \pi N, \eta N, \rho N, \pi\Delta, \sigma N$ and $\pi N^*(1440)$. The main approximations are the incomplete representation of the left-hand cuts and the quasi-two-body treatment of 3-body final states. Since the background is parametrized by distant unphysical poles specific to each partial wave, separate fits are performed for each partial wave.

2.3 The KSU model

The Kent State approach is a generalization of the multichannel Breit-Wigner representation to include an arbitrary number of resonances plus nonresonant background. The method treats background empirically by using a product S-matrix so that the total S matrix is given by $S = B^T RB$, where B is a unitary background matrix (not generally symmetric), R is the [symmetric] S-matrix in the absence of all background, and B^T is the transpose of B. Background couplings having the proper threshold behavior (analogous to partial widths) may be introduced for each channel, providing a great deal of flexibility. Resonance poles can be extracted but dispersion relations are not incorporated explicitly; gauge invariance is not assured in this approach. The Kent State method has been successfully applied to the simultaneous description of πN elastic scattering, pion photoproduction, and various quasi-two-body $\pi\pi N$ channels, such as $\rho N, \pi\Delta, \sigma N$ and $\pi N^*(1440)$. Additional channels such as ηN and $K\Lambda$ can be included when necessary to satisfy unitarity.

3 Results and Discussion

In general, the fits performed by the Pitt-ANL and KSU groups achieve an excellent description of the experimental phase shifts and multipoles, reflecting the flexibility of their phenomenological background with separate parameter sets for each partial wave. The GW-Giessen fits are very good for most partial waves but do encounter significant deviations from experiment for a few partial waves in selected energy regimes. This can be traced to the nonresonant terms that define the background through a small set a Feynman diagrams with few parameters, thus providing less flexibility. The Pitt-ANL analysis extracts properties of 27 N^* states, the KSU includes 24 and the GW-Giessen effort analyzes 16 N^* resonances. Here we point out some general patterns identified and discuss a few specific partial waves. The N^* states naturally sort themselves into separate categories when discussed in terms of the first, second and third N^* *in each partial wave.* Most properties of most first-tier resonances, such as their mass, total width, partial widths and helicity amplitudes were found to be in agreement with each other at the 20-30% level. In the I=1/2 sector this includes, for example, the $P_{11}(1440)$, $D_{13}(1520)$, $D_{15}(1675)$, and $F_{15}(1680)$ states; in the I=3/2 sector one finds, e.g., the $P_{33}(1232)$, $D_{33}(1700)$, $P_{31}(1910)$ and $F_{37}(1950)$ states (note that for spin 5/2 and 7/2 states only the Pitt-ANL and KSU results can be compared with each other). In most cases, these first-tier (virtually all of them 4-star according to the PDG rating system) states are fairly isolated, cleanly separated resonances with typical Breit-Wigner behavior and small background; exceptions are the $S_{31}(1620)$ and $P_{13}(1720)$ states. For second-tier states, rough agreement is found only for the resonance mass, while the extracted total and partial widths vary widely in most cases. Examples are the $P_{33}(1600)$, $P_{11}(1710)$, $D_{13}(1700)$ and $P_{13}(1900)$. Finally, the very existence of third-tier states in each partial wave is tenuous at best. Since for most second- and third-tier resonances the coupling to the elastic πN channel is weak, they require significant input from inelastic channels. For second-tier states, available inelastic data are of poor quality and for third-tier states, the data are almost nonexistent.

3.1 Resonances in the S_{11}, D_{13} and P_{13} partial waves

The S_{11} partial wave have long been recognized as an unusual partial wave, with two strongly interfering resonances in close proximity to each other and to the ηN threshold. Since any multi-resonance, coupled-channels framework naturally includes these features, the three analyses are in fair agreement with each other for most of the $S_{11}(1535)$ properties, listed in Table 1. Exceptions are the total width where the GW-Giessen result around 250 MeV is considerably larger (closer to single-channel extractions[6]), and the KSU $A^p_{1/2}$ helicity amplitude which with 0.042 $\mathrm{GeV}^{-1/2}$ is much smaller compared to the results of the other two analyses. The latter is due to the fact that KSU has not yet included the eta photoproduction data in their fit. It is known that analyses based solely on pion photoproduction consistently underestimate this quantity

Table 1. Selected nucleon resonance parameters for the S_{11} partial wave. The first (second, third) line shows the results from GW-Giessen (KSU, Pitt-ANL). For the first set, estimated ranges are given representing systematic model uncertainties, while the latter two sets show standard statistical uncertainties. GW-Giessen did not find a third S_{11} state. (^{a}) *obtained without ηN production data in the fit.*

	$S_{11}(1535)$	$S_{11}(1650)$	$S_{11}(2090)$
M (MeV)	1542-1556 1528(1) 1542(3)	1679-1701 1649(1) 1689(12)	- 2000(1) 1822(43)
Γ_{tot} (MeV)	213-252 111(9) 112(19)	194-219 108(14) 202(40)	- 132(16) 248(185)
Γ_π (%)	29-31 41(3) 35(4)	63-77 32(5) 74(2)	- 10(3) 17(7)
Γ_η (%)	60-66 $50(4)^a$ 51(5)	10-12 $5(3)^a$ 6(1)	- $3(2)^a$ 41(4)
$A^p_{1/2}$ (10^{-3} GeV$^{-1/2}$)	101-111 $42(6)^a$ 87(3)	35-46 $17(7)^a$ 48(9)	- $39(17)^a$ -

(around 0.060 GeV$^{-1/2}$ or lower) while extractions which include the (γ, η) data place the value closer to 0.10 GeV$^{-1/2}$. The results are less stable for the $S_{11}(1650)$; here the KSU results for Γ_{tot}, Γ_π, and $A^p_{1/2}$ are considerably lower than the ranges found by GW-Giessen and Pitt-ANL. The new (γ, η) GRAAL data at higher energy[7,8], included in the GW-Giessen analysis, suggest a Γ_η of 10-12%, higher than previously quoted. Finally, there is clearly no agreement with regard to the existence and location of a third S_{11} state. Figure 1 shows that all three analyses produce surprisingly similar backgrounds for the E_{0+}, despite the rather different model inputs. For the imaginary part the KSU background is larger in the region of the second S_{11}, which explains the lower KSU values for the $S_{11}(1650)$.

The $D_{13}(1520)$ state is a first-tier resonance with a clear signal in both πN phase and (γ, π) multipoles, as shown in Fig. 1. The three analyses agree fairly well on its hadronic properties (see Table 2), whereas for both helicity couplings the GW-Giessen values lie significantly below the results from the two other groups. We point out that recent single-channel (γ, η) fits[9] find a much larger (negative) value of $A^p_{1/2} = -0.078$ GeV$^{-1/2}$ when the new GRAAL data are included. The second D_{13} decouples almost totally from the πN channel, as found in all three analyses. For this state, the $\pi\Delta$ channel represents the dominant decay mode. All three groups find some evidence for a third D_{13} state around 1900-2000 MeV with a very large total width. This state has recently been implicated[10] to play a major role in the reaction $\gamma p \to K^+\Lambda$, where new cross-section data revealed a structure around 1900 MeV. Displayed in Fig. 1, the M_{2-} background terms are very similar below 1500 MeV but significant differences appear in the real part at higher energies between GW-Giessen and KSU results compared to the Pitt-ANL results.

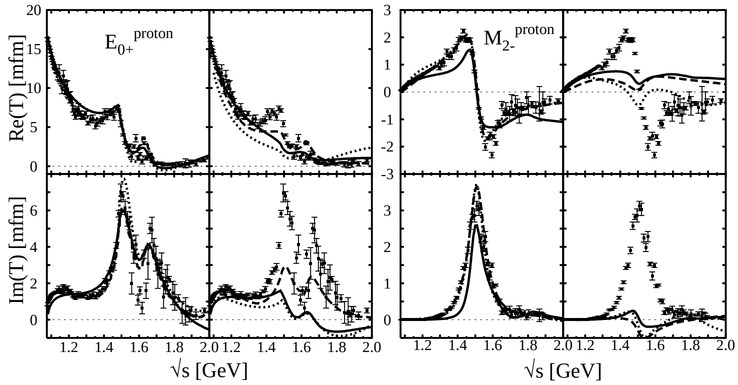

Figure 1. The pion photoproduction E_{0+} and M_{2-} proton multipoles. The solid (dashed, dotted) curves show the results of the GW-Giessen (KSU, Pitt-ANL) analysis. For each multipole the left-hand panels show the full calculation while the right-hand panels show the background contributions only.

As an exception we discuss the $P_{13}(1720)$, designated as a 3-star resonance by the PDG. Figure 2 displays this partial wave with an unusual background and a weak resonance signal. Large differences appear between the three analyses, but no clear pattern emerges. For the real part of the M^{proton}_{1+}(I=1/2) the GW-Giessen and KSU backgrounds closely follow the data, quite different from the Pitt-ANL background. On the other hand, for the real part of the E^{proton}_{1+}(I=1/2) the KSU and Pitt-ANL results tend to agree with each other while the GW-Giessen result follows the data. The imaginary parts of both multipoles display large differences between all three models, especially at higher energies. These variations are reflected in the wide range of values extracted for the $P_{13}(1720)$ properties, listed in Table 2. This level of instability for the fitting results resembles the behavior of second-tier, rather

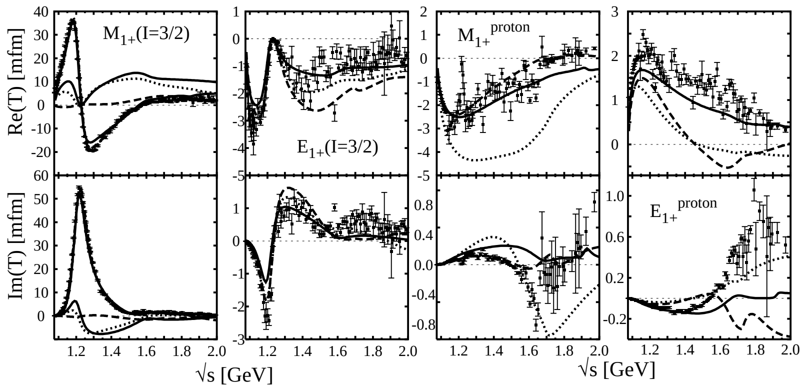

Figure 2. The pion photoproduction M_{1+} and E_{1+} multipoles. Notation of the curves as in Fig. 1. Background contributions are shown for I=3/2 (left two plots) and I=1/2 (right two plots). The full calculations are also shown for the M_{1+} (I=3/2) multipole.

Table 2. Selected nucleon resonance parameters for the D_{13} and P_{13} partial wave. The first (second, third) line shows the results from GW-Giessen (KSU, Pitt-ANL). The helicity amplitudes are given in units of 10^{-3} GeV$^{-1/2}$. Pitt-ANL did not find a second P_{13} state. (^{b}) *preliminary results.*

	$D_{13}(1520)$	$D_{13}(1700)$	$D_{13}(2080)$	$P_{13}(1720)$	$P_{13}(1900)$
M (MeV)	1506-1512 1521(1) 1518(3)	1690 1662(1) 1736(33)	1912 2003(1) 2003(18)	1771-1809 1720(18) 1716(112)	1987 1919(26) -
Γ_{tot} (MeV)	84-110 120(4) 124(4)	202 $509(30)^b$ 175(133)	598 698(35) 1070(858)	344-637 246(52) 121(39)	531 569(127) -
Γ_π (%)	53-59 56(2) 63(2)	<1 $<1^b$ 4(2)	8 26(2) 13(3)	20-22 17(1) 5(5)	10 16(3) -
$A^p_{1/2}$	(-9)-$(+2)$ $-18(5)$ $-25(6)$	3 $-121(45)^b$ $-47(9)$	-15 $-20(12)$ $-6(33)$	23-36 70(11) 50(16)	10 122(21) -
$A^p_{3/2}$	134-152 207(13) 171(7)	42 $-458(89)^b$ 74(7)	7 $-99(22)$ 174(36)	23-75 $-45(10)$ 17(26)	43 $-75(19)$ -

than first-tier, resonances. This impression is supported when one examines the $P_{13}(1900)$, which behaves like a third-tier state: not even its existence is confirmed in all three analyses. These exceptions to the "first-tier rule" clearly demand a deeper understanding of the differences between the various background models. To emphasize this point, Fig. 2 also displays the differences between backgrounds for the extensively studied partial waves M_{1+} and E_{1+} with I=3/2. Especially for the M_{1+} around W=1232 MeV KSU finds a very small brackground in contrast to GW-Giessen and Pitt-ANL. Since the $P_{33}(1232)$ has the "luxury" of Watson's theorem as a way to enforce unitarity, all backgrounds vanish at the resonance position; this is clearly not the case for the higher-lying P_{33} states.

4 Conclusions and Outlook

We conclude by posing a number of questions that future refinements of these models and their comparison with each other will have to address:

- *How many N^* states do we need to identify?* The answer clearly depends on the partial wave and on the theoretical description being used. On average, we would suggest that three N^* per partial wave should be sufficient, with lower partial waves like the S_{11} and P_{11} possibly requiring 4-5 states in order to settle the question of the "missing resonances", while only two resonances may need to be studied for higher partial waves.
- *What form of resonance vertices and propagators are needed for high-spin resonances?* For N^* states with spin greater than 1/2, do we need the full Lorentz and Dirac spin structure as demanded by field theory or do we "get away" with simple Breit-Wigner parametrizations? Indications from first-tier states with spin 3/2 like the $P_{33}(1232)$ and $D_{13}(1520)$ are that one extracts similar properties either way. However, it is not clear yet if differences for some of the higher-lying states are due to this feature. Should the full Dirac structure be required, this would complicate the extraction of the properties of states with spin 5/2 and higher.
- *What is the proper background description?* Since the extraction of resonance properties is inexorably linked to the separation of background from resonance terms this question has an immediate impact. The concern here is that in the case of a very weak signal from a broad resonance superposed on a large, complicated background, too flexible a parametrization might lead to extracting wrong N^* properties or even erase the resonance signal altogether. If this problem were valid one

would have expected to find large differences between the field-theoretical background from GW-Giessen on the one side, and the empirical backgrounds of the KSU and Pitt-ANL groups on the other side. What was found in this study, however, are rather similar background contributions in many cases, with some notable exceptions that did not follow any clear pattern.

Future studies will focus in more detail on the question of data dependency by using a uniform data base. The model dependencies to resonance and background parametrizations within and across different analysis methods will also be studied more closely; this issue has already been looked at by Pitt-ANL[3] for the S_{11} channel. We expect that such efforts will lead to a solid understanding of first-tier resonances, using exceptions like the $P_{13}(1720)$ to provide a clearer picture of the background. These findings, together with an improved data base for the inelastic channels, should help pave the way for a deeper understanding of the second- and third-tier N^* states as well.

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