NOTE ON N AND Δ RESONANCES

Written December 1997 by R.L. Workman (Virginia Polytechnic Institute and State University).

I. Introduction

The excited states of the nucleon have been studied in a large number of formation and production experiments. The conventional (Breit-Wigner) masses, pole positions, widths, and elasticities of the N and Δ resonances in the Baryon Summary Table come almost entirely from partial-wave analyses of πN total, elastic, and charge-exchange scattering data. Partial-wave analyses have also been performed on much smaller data sets to get $N\eta$, ΛK, and ΣK branching fractions. Other branching fractions come from isobar-model analyses of $\pi N \to N\pi\pi$ data. Finally, many $N\gamma$ branching fractions have been determined from photoproduction experiments.

Table 1 lists all the N and Δ entries in the Baryon Listings and gives our evaluation of the status of each, both overall and channel by channel. Only the "established" resonances (overall status 3 or 4 stars) appear in the Baryon Summary Table. We consider a resonance to be established only if it has been seen in at least two independent analyses of elastic scattering and if the relevant partial-wave amplitudes do not behave erratically or have large errors.

Two changes have been made in the Baryon Summary Table: The $\Delta(1900)$ S_{31} state has been downgraded from three stars to two due to its weak signal in speed plots, and thus has been dropped from the Table. More importantly, pole parameters have been added to the Table, as these tend to be less model dependent than parameters found in fits using generalized Breit-Wigner formulas. This point is the subject of the next section.

Table 1. The status of the N and Δ resonances. Only those with an overall status of ∗∗∗ or ∗∗∗∗ are included in the main Baryon Summary Table.

Particle	$L_{2I\cdot 2J}$	Overall status	Status as seen in —						
			$N\pi$	$N\eta$	ΛK	ΣK	$\Delta\pi$	$N\rho$	$N\gamma$
$N(939)$	P_{11}	∗∗∗∗							
$N(1440)$	P_{11}	∗∗∗∗	∗∗∗∗	∗			∗∗∗	∗	∗∗∗
$N(1520)$	D_{13}	∗∗∗∗	∗∗∗∗	∗			∗∗∗∗	∗∗∗∗	∗∗∗∗
$N(1535)$	S_{11}	∗∗∗∗	∗∗∗∗	∗∗∗∗			∗	∗∗	∗∗∗
$N(1650)$	S_{11}	∗∗∗∗	∗∗∗∗	∗	∗∗∗	∗∗	∗∗∗	∗∗	∗∗∗
$N(1675)$	D_{15}	∗∗∗∗	∗∗∗∗	∗	∗		∗∗∗∗	∗	∗∗∗∗
$N(1680)$	F_{15}	∗∗∗∗	∗∗∗∗				∗∗∗∗	∗∗∗∗	∗∗∗∗
$N(1700)$	D_{13}	∗∗∗	∗∗∗	∗	∗∗	∗	∗∗	∗	∗∗
$N(1710)$	P_{11}	∗∗∗	∗∗∗	∗∗	∗∗	∗	∗∗	∗	∗∗∗
$N(1720)$	P_{13}	∗∗∗∗	∗∗∗∗	∗	∗∗	∗	∗	∗∗	∗∗
$N(1900)$	P_{13}	∗∗	∗∗					∗	
$N(1990)$	F_{17}	∗∗	∗∗	∗	∗	∗			∗
$N(2000)$	F_{15}	∗∗	∗∗	∗	∗	∗	∗	∗∗	
$N(2080)$	D_{13}	∗∗	∗∗	∗	∗				∗
$N(2090)$	S_{11}	∗	∗						
$N(2100)$	P_{11}	∗	∗	∗					
$N(2190)$	G_{17}	∗∗∗∗	∗∗∗∗	∗	∗	∗		∗	∗
$N(2200)$	D_{15}	∗∗	∗∗	∗	∗				
$N(2220)$	H_{19}	∗∗∗∗	∗∗∗∗	∗					
$N(2250)$	G_{19}	∗∗∗∗	∗∗∗∗	∗					
$N(2600)$	$I_{1\,11}$	∗∗∗	∗∗∗						
$N(2700)$	$K_{1\,13}$	∗∗	∗∗						

$\Delta(1232)$	P_{33}	****	****	F					****
$\Delta(1600)$	P_{33}	***	***	o			***	*	**
$\Delta(1620)$	S_{31}	****	****	r			****	****	***
$\Delta(1700)$	D_{33}	****	****	b		*	***	**	***
$\Delta(1750)$	P_{31}	*	*	i					
$\Delta(1900)$	S_{31}	**	**	d		*	*	**	*
$\Delta(1905)$	F_{35}	****	****	d		*	**	**	***
$\Delta(1910)$	P_{31}	****	****	e		*	*	*	*
$\Delta(1920)$	P_{33}	***	***	n		*	**		*
$\Delta(1930)$	D_{35}	***	***			*			**
$\Delta(1940)$	D_{33}	*	*	F					
$\Delta(1950)$	F_{37}	****	****	o		*	****	*	****
$\Delta(2000)$	F_{35}	**		r				**	
$\Delta(2150)$	S_{31}	*	*	b					
$\Delta(2200)$	G_{37}	*	*	i					
$\Delta(2300)$	H_{39}	**	**	d					
$\Delta(2350)$	D_{35}	*	*	d					
$\Delta(2390)$	F_{37}	*	*	e					
$\Delta(2400)$	G_{39}	**	**	n					
$\Delta(2420)$	$H_{3\,11}$	****	****						*
$\Delta(2750)$	$I_{3\,13}$	**	**						
$\Delta(2950)$	$K_{3\,15}$	**	**						

**** Existence is certain, and properties are at least fairly well explored.
*** Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, *etc.* are not well determined.
** Evidence of existence is only fair.
* Evidence of existence is poor.

No new elastic partial-wave analyses have been published since our last *Review*, although some preliminary results were reported at MENU 97 [1], which also contains recent studies of the πN σ term, scattering lengths, and possible isospin-breaking effects.

Several inelastic scattering analyses are now underway [2–5]. Most of them use $\pi N \rightarrow N\eta$ data, together with $\pi N \rightarrow \pi N$ data, in order to obtain improved values of the properties of the $N(1535)$ S_{11}. The Pittsburgh-ANL [2] and Giessen [3] coupled-channel analyses are similar in scope to that of Manley and Saleski [6], but they differ in theoretical approach and in also using electromagnetic channels.

The interested reader will find further discussions in the proceedings of two recent conferences [7,1], and in two older reviews [8,9].

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II. Against Breit-Wigner parameters — a pole-emic

Written December 1997 by G. Höhler (University of Karlsruhe).

(1) All theoretical approaches to the resonance phenomenon have in common that the variation of a partial-wave amplitude $T(W)$, where W is the total c.m. energy, is related to a nearly bound state of the projectile-target system (see *e.g.*, Refs. [1–5]). In πN scattering, this state is an excited state of the nucleon (= isobar). The nearly bound state is described in the framework of S-matrix theory by a pole of the S-matrix element at $W_p = M - i\Gamma/2$ in the lower half of the complex W-plane, close to the real axis; M and Γ are called the mass and width of the resonance. The location of the resonance pole is the same for all reactions to which the resonance couples.

In the inelastic region, a resonance is associated with a cluster of poles on different Riemann sheets. If one of these poles is located near the real axis and sufficiently far from branch points, it will be strongly dominant. If one of the final-state particles itself has a strong decay, one also has to consider branch points in the lower half plane that belong to thresholds for two-particle final states (see *e.g.*, Refs. [6,7]).

(2) If the formation of an unstable intermediate particle occurs in a scattering process, one expects *a time-delay between the arrival of the incident wave packet and its departure from the collision region*. Goldberger and Watson [8], starting from earlier work by Wigner, derived for elastic scattering the time-delay Q. Expressed in terms of the amplitude $T(W)$, it is $Q = 2\,Sp(W)$, where $Sp(W) = |dT/dW|$ is the *speed* with which the complex vector T traverses the Argand diagram. If the background can be neglected, a resonance pole leads to a peak of $Sp(W)$ at $W = M$ (see the cited books and Refs. [9–11]).

(3) It is an old tradition that authors of partial-wave analyses determine *conventional resonance parameters* from fits to generalized Breit-Wigner formulas. Each group has its own prescription for the treatment of analyticity, the choice of the background, and other details, so the model-dependence is much larger than in the determination of pole parameters. A serious

shortcoming is the poor or missing information on inelastic channels. The conventional parameters are the "mass" m, the "width" $\Gamma(W)$ at $W = m$, and the branching ratios. Following are some problems with these parametrizations.

(a) The conventional $\Delta(1232)$ parameters come from a fit to the P33 partial wave. It is well known from the Chew-Low plot and dispersion relations [12] that this partial wave has a *large background from the nucleon pole term*. The pole position, $1210 - 50\,i$ MeV, belongs to the Δ-resonance, whereas the conventional parameters, $m = 1232$ MeV and $\Gamma(m) = 120$ MeV, belong to the Δ *together with the large background in πN scattering.*

(b) The $N(1535)$ S_{11} is *the only 4-star resonance that does not show a signal in the speed plot.* The signal is probably part of the large peak due to the threshold for η production [13]. In this case, poles in other Riemann sheets are expected to give contributions of comparable magnitude. One of these poles produces the threshold cusp [6]. In the 1960's, this problem was treated in many papers (see Ref. 13). In calculations that rely on the conventional mass of 1535 MeV, one cannot see that one has to study a combined resonance plus threshold-cusp phenomenon.

A similar situation of poles in different sheets arises in $\pi\pi$ scattering near the $K\bar{K}$ threshold. See remarks in footnotes to our $f_0(980)$ Listing.

(c) Around 1440 MeV, the VPI group found *two poles in the P_{11} amplitude in different Riemann sheets* [14]. This was interpreted, by other authors, as evidence for the existence of two nearly degenerate P_{11} resonances, in conflict with the constituent quark model. Cutkosky pointed out that the branch point for $\Delta\pi$ decay is located near the poles, so the poles belong to the same resonance. This was confirmed by a new calculation [15], which also led to conventional parameters of $m = 1471$ MeV and $\Gamma(m) = 545$ MeV, which are *much different from the pole parameters*, $1370 - 114\,i$ and $1360 - 120\,i$ MeV. The speed plot confirms that the formation of the unstable particle $N(1440)$ P_{11} occurs at a considerably lower energy than expected from the conventional parameters.

Conclusion: *In contrast to the conventional parameters, the pole positions and speed plots have a well-defined relation to S-matrix theory. They also give more information on the resonances and thresholds and can be used for predictions on other reactions that couple to the excited states.*

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III. Electromagnetic interactions

Revised December 1997 by R.L. Crawford (University of Glasgow) and R.L. Workman (Virginia Polytechnic Institute and State University).

Nearly all the entries in the Listings concerning electromagnetic properties of the N and Δ resonances are $N\gamma$ couplings. These couplings, the helicity amplitudes $A_{1/2}$ and $A_{3/2}$, have been obtained in partial-wave analyses of single-pion photoproduction, η photoproduction, and Compton scattering. Most photoproduction analyses take the existence, masses, and widths of the resonances from the $\pi N \to \pi N$ analyses, and only determine the $N\gamma$ couplings. A brief description of the various methods of analysis of photoproduction data may be found in our 1992 edition [1].

Our Listings omit a number of analyses that are now obsolete. Most of the older results may be found in our 1982 edition [2]. The errors quoted for the couplings in the Listings are calculated in different ways in different analyses and therefore should be used with care. In general, the systematic differences between the analyses caused by using different parameterization schemes are probably more indicative of the true uncertainties than are the quoted errors.

Probably the most reliable analyses, for most resonances, are ARAI 80, CRAWFORD 80, AWAJI 81, FUJII 81, CRAWFORD 83, and ARNDT 96. The $\Delta(1232)$ and $N(1535)$ are special cases, discussed separately below. The errors we give are a combination of the stated statistical errors on the analyses and the systematic differences between them. The analyses are given equal weight, except ARNDT 96 is weighted, rather arbitrarily, by a factor of two because its data set is at least 50% larger than those of the other analyses and contains many new high-quality measurements. Again, the $\Delta(1232)$ and $N(1535)$ are discussed separately below.

The Baryon Summary Table gives $N\gamma$ branching fractions for those resonances whose couplings are considered to be reasonably well established. The $N\gamma$ partial width Γ_γ is given in terms of the helicity amplitudes $A_{1/2}$ and $A_{3/2}$ by

$$\Gamma_\gamma = \frac{k^2}{\pi}\frac{2M_N}{(2J+1)M_R}\left[|A_{1/2}|^2 + |A_{3/2}|^2\right] \quad . \qquad (1)$$

Here M_N and M_R are the nucleon and resonance masses, J is the resonance spin, and k is the photon c.m. decay momentum.

New results for $\boldsymbol{\Delta(1232) \to p\gamma}$***:*** Recent measurements of $\gamma p \to N\pi$ and $\gamma p \to \gamma p$ have fueled a number of new analyses across the first resonance region [3–7]. A central focus has been the E2/M1 ratio, evaluated at the K-matrix and T-matrix poles. The electric quadrupole ($E2$) and magnetic dipole ($M1$) amplitudes are related to our helicity amplitudes by

$$A_{1/2} = -\frac{1}{2}(M1 + 3E2) \quad \text{and} \quad A_{3/2} = -\frac{\sqrt{3}}{2}(M1 - E2) \ . \quad (2)$$

Most recent estimates of the E2/M1 ratio, evaluated at the K-matrix pole, are considerably larger (in magnitude) than the average, $-1.5 \pm 0.4\%$, quoted in our 1996 *Review.* This quantity is quite sensitive to the database being fitted. Fits that exclude a few of the older Bonn measurements [8] tend to fall in the range $-2.5 \pm 0.5\%$. (Some analyses of the recent Mainz and BNL measurements suggest a central value closer to -3% [3,7].) The E2/M1 ratio appears to be relatively stable when evaluated at the T-matrix pole [9]. This ratio of pole residues has been added to the Full Listings [10].

Values of $A_{1/2}$ and $A_{3/2}$ from the RPI [3] and VPI [4] analyses are in reasonable agreement. However, the BNL [7] results are quite different, due to their larger cross sections for $\pi^0 p$ photoproduction. Previous estimates of the E2 and M1 amplitudes, at the K- and T-matrix poles, should be considered obsolete. Pole parameters given for the $\Delta^+(1232)$ in our 1996 *Review* are also obsolete (see Ref. [11]).

New results for $\boldsymbol{N(1535) \to p\gamma}$***:*** Properties of the $N(1535)$ are difficult to extract from $\pi N \to \pi N$ and $\gamma N \to \pi N$ due to the nearby ηN threshold (see Sec. III). As a result, a number of recent analyses have been based on data from $\pi^- p \to \eta n$ and $\gamma p \to \eta p$. These studies, and those based on coupled-channel analyses including pion photoproduction data, generally find results [12–15] for $A_{1/2}$ that are significantly different from those based on pion photoproduction alone. In particular, $A_{1/2}$ is sensitive to the $N(1535)$ mass and width, and to its interference with the $N(1650)$ [15].

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IV. Outlook

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In May 1997, a new program in baryon spectroscopy was initiated at the Brookhaven National Laboratory AGS with the Crystal Ball Spectrometer [1]. AGS Expt. E913 measures over most of a 4π solid angle the reactions $\pi^- p \to \gamma n$, $\pi^0 n$, ηn, and $\pi^0\pi^0 n$ at 12 momenta between 285 and 750 MeV/c. These measurements will be completed in 1998, and then AGS Expt. E914 will begin a study of hyperon resonances using the reactions $K^- p \to$ neutrals.

Most of the new generation of experiments to study baryon spectroscopy will use electromagnetic probes. Commissioning experiments were carried out for the CEBAF Large Acceptance Spectrometer, CLAS, during mid 1997, using electron beams with energies of 1.6, 2.4, and 4.0 GeV. The first physics run began in December 1997. Initial measurements of $ep \to eX$ will be performed with 1.6- and 2.4-GeV electrons. Measurements with 4.0-GeV electrons are scheduled for early 1998. Runs with tagged photons are scheduled for early Spring and Summer, 1998. A number of experiments at CEBAF to study baryon resonances have already been completed, including studies of the $(e, e'K^+)$ reactions on hydrogen and deuterium targets [2], and studies of the $e^- p \to e^- p\eta$ reaction [3]. The $E2/M1$ ratio is being investigated using new measurements of the $p\,(e, e'p)\pi^0$ reaction near the $\Delta(1232)$ resonance, and new measurements of $p(e, e'\vec{p})\pi^0$ at the MIT-Bates Lab [4].

Much work is also underway in European facilities. For example, in 1996, studies of η and K photoproduction commenced at GRAAL in Grenoble [5]. This lab currently provides photon beams with energies up to 1.5 GeV, and may later upgrade to 1.8 GeV. Several reactions are under study there, including $\gamma p \to \gamma p$, ηp, $\pi^0 p$, $\pi^+ n$, and $\pi^0\pi^0 p$. New meson photoproduction data are also being produced from experiments using the 855-MeV CW electron accelerator MAMI at Mainz, which produces photon beams with energies up to 800 MeV [6]. For example, new experiments of pion photoproduction with linearly polarized photons having energies up to 500 MeV are providing data on the $E2/M1$ ratio for the $\Delta(1232)$ resonance.

Space does not permit a full discussion of the large amount of experimental work now underway at the labs already mentioned, or at other labs such as Bonn. The new experiments have also inspired many new theoretical and phenomenological efforts to understand this particular aspect of nonperturbative QCD. These efforts include techniques such as lattice gauge theory, phenomenological Lagrangians, constituent quark-model calculations, and various unitary multichannel approaches.

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V. Non-*qqq* baryon candidates

The standard quark-model assignments for baryons are outlined in Sec. 13.3, "Baryons: *qqq* states." Just as with mesons (see the "Note on Non-$q\bar{q}$ mesons"), there have been suggestions that non-*qqq* baryons might exist, such as hybrid (*qqqg*) baryons and unstable meson-nucleon bound states [1] (see the "Note on the $\Lambda(1405)$").

If non-*qqq* states exist, they will be more difficult to identify than hybrid mesons: They will not have the clean signature of exotic quantum numbers, and they should also mix with ordinary *qqq* states. Their identification will depend upon (a) characteristics of their formation and decay, and (b) an over-population of expected *qqq* states.

Most investigations have focused on the properties of the lightest predicted hybrids. If the first hybrid state lies below 2 GeV, as is suggested by bag-model calculations [2,3,4], it may already exist in our Listings. (However, some estimates put the lightest state well above 2 GeV [5].) At present, there are actually not enough known resonances to fill the known multiplets. If an existing resonance is identified as a hybrid, yet another ordinary *qqq* state must be found.

The Roper resonance, the $N(1440)\,P_{11}$, has been a hybrid candidate based upon its quantum numbers [2] and difficulties with its mass and electromagnetic couplings. If it were a hybrid, our interpretation of the low-lying P_{11}, P_{13}, P_{31}, and P_{33} resonances would change [2,6]. In Ref. 6, both the $N(1440)\,P_{11}$ and $\Delta(1600)\,P_{33}$ are hybrid candidates, and $N(1540)\,P_{13}$ and $\Delta(1550)\,P_{31}$ states are predicted. One-star P_{13} and P_{31} states were listed in our 1990 Review [7] but were then removed.

Both photoproduction [6,8,9] and electroproduction [9,10] have been considered in the search for a unique hybrid signature. In Ref. 11, QCD counting rules were used to reveal a characteristic of hybrid electroproduction at high Q^2. If the $N(1440)$ is a hybrid, its transverse form factor is expected to fall asymptotically $\mathrm{O}(1/Q^2)$ faster than for a pure *qqq* state. However, mixing between *qqq* and *qqqg* states will make this identification difficult.

A number of recent experiments have searched for pentaquark ($qqqq\bar{q}$) resonances and H dibaryons ($uuddss$ states). Narrow structures found in proton-nucleus scattering [12] have been attributed to $qqqs\bar{s}$ states, but these need confirmation. The H-dibaryon experiments, while finding possible candidates [13], have generally quoted upper limits [14] for exotic resonance production. Searches for narrow dibaryons in the nucleon-nucleon interaction are also continuing [15].

Finally, there has been a report [16] of resonances lying below the $\Delta(1232)$. A very weak signal was found using the reaction $pp \to \pi^+ p X^0$. An earlier search [17] for isospin-3/2 states, using $pp \to n X^{++}$, found a null result in the mass range between M_N and $M_N + M_\pi$. At present, there appears to be no evidence for such low-mass states from other reactions.

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