N AND Δ RESONANCES

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I. Introduction

The excited states of the nucleon have been studied in a large number of formation and production experiments. The conventional (*i.e.,* Breit-Wigner) masses, pole positions, widths, and elasticities of the N and Δ resonances in the Baryon Summary Table come largely 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 (see Sec. III).

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 generally 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.

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 edition. Preliminary new results from the Virginia Tech group were reported at MENU 99 [1]; this reference also reports recent studies of the πN sigma term, scattering lengths, and possible isospin-breaking effects. Two extensions of an earlier [2] multi-channel analysis have appeared since our last edition. The first [3] extracted pole positions and residues for the $N(1535)$ and $N(1650)$. The second [4] added $\gamma N \to N\pi$ multipoles to the previous set of $\pi N \to N\pi$, $\pi N \to N\eta$ and $\gamma N \to N\eta$ data and amplitudes.

The interested reader will find further discussions in the proceedings of three recent conferences [1,5,6], and in two older reviews [7,8].

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

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(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. [9–13]). 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. [14,15]).

(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 [16], 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. [17–19]).

(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 [20] 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 [21]. In this case, poles in other Riemann sheets are expected to give contributions of comparable magnitude. One of these poles produces the threshold cusp [14]. In the 1960's, this problem was treated in many papers (see Ref. 21). 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 $K\overline{K}$ 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* [22]. 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 [23], 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.

III. Electromagnetic interactions

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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 have taken the existence, masses, and widths of the resonances from the $\pi N \to \pi N$ analyses, and have only determined the $N\gamma$ couplings. This approach is only applicable to resonances with a significant $N\pi$ coupling. A brief description of the various methods of analysis of photoproduction data may be found in our 1992 edition [24].

Our Listings omit a number of analyses that are now obsolete. Most of the older results may be found in our 1982 edition [25]. 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. Several special cases are 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. The $\Delta(1232)$ and $N(1535)$ are special cases, discussed 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

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

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 $\Delta(1232) \rightarrow p\gamma$: Recent studies of the $\Delta(1232)$ have focussed on the problem of separating background from resonance, and on the $E2/M1$ ratio at nonzero values of Q^2. The electric quadrupole ($E2$) and magnetic dipole ($M1$) amplitudes are related to our helicity amplitudes by

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

Problems associated with the $E2/M1$ ratio at $Q^2 = 0$ [26] were discussed in our 1998 Review [27].

The $E2/M1$ ratio has been given at $\mathrm{Q}^2 = 2.8$ and 4.0 $(\mathrm{GeV/c})^2$, based on analyses of Jefferson Lab $p(e, e'p)\pi^0$ data [28], and at 3.2 $(\mathrm{GeV/c})^2$, based on a re-analysis of older DESY measurements [29]. Results are not yet stable, and depend upon the method employed. This is particularly evident in analyses of the DESY measurements, which have resulted in $E2/M1$ ratios differing in both sign and magnitude [28,30,31].

Results for the $E2/M1$ ratio at $\mathrm{Q}^2 = 2.8$ and 4.0 $(\mathrm{GeV/c})^2$ are 0.039 ± 0.029 and 0.04 ± 0.031 from Ref. 30, compared to $-0.020 \pm 0.012 \pm 0.005$ and $-0.031 \pm 0.012 \pm 0.005$ from Ref. 28. Notice the difference in sign. There is general agreement that the ratio remains small relative to the perturbative QCD expectation that $E2/M1$ should approach unity.

The method [32] used in Ref. 30 gives values for the $\mathrm{Q}^2 = 0$ $N\gamma$ amplitudes, $A_{1/2}$ and $A_{3/2}$, that are about 30% smaller (in magnitude) than our previous estimates. While this shift improves agreement with quark models, there is no consensus on its validity [26].

The ratio of scalar quadrupole and magnetic dipole amplitudes (S_{1+}/M_{1+}) is also problematic. A previous fit [33] to the DESY measurements gave 0.07±0.02±0.03 at Q^2=3.2 (GeV/c)^2. This disagrees with a recent fit [28] to the Jefferson Lab data, $-0.112 \pm 0.013 \pm 0.01$ and $-0.148 \pm 0.013 \pm 0.01$ at Q^2=2.8 and 4.0 (GeV/c)^2, and with a fit [30] to both DESY and Jefferson Lab data sets, -0.049 ± 0.029, -0.099 ± 0.041, and -0.085 ± 0.021 at Q^2=2.8, 3.2, and 4.0 (GeV/c)^2.

New results for $p\eta$: Fits to η-photoproduction data have given $N\gamma$ amplitudes for the $N(1535)$ that are substantially larger than those extracted from fits to π-photoproduction data (see the 1998 Review [27] for details). More recent analyses [34,35] have considered the sensitivity of this reaction to contributions from the $N(1520)$. The ratio of $N(1520) \to N\gamma$ amplitudes, $A_{3/2}/A_{1/2}$, was found to be $-2.5 \pm 0.5 \pm 0.4$ in Ref. 34 and -2.1 ± 0.2 in Ref. 35. Results inferred from π-photoproduction are about a factor of three larger in magnitude (see the Particle Listings). The η-photoproduction result is particularly surprising, as the $N(1520)$ has a very clean resonance signature in π photoproduction.

Recent $p(e,e'p)\eta$ cross-section measurements [36] have been fitted to extract the $N(1535)$ transition amplitude. Values for $A_{1/2}$ are 0.050±0.007 GeV$^{-1/2}$ at 2.4 (GeV/c)^2 and 0.035±0.005 GeV$^{-1/2}$ at 3.6 (GeV/c)^2. These are in qualitative agreement with the results of Ref. 37.

New results for $p\eta'$: A fit to SAPHIR total and differential cross sections has been made [38], assuming resonance dominance and taking only S- and P-wave multipoles. The extracted resonance parameters are $S_{11}(M,\Gamma) = (1897 \pm 50^{+30}_{-2}, 396 \pm 115^{+35}_{-45})$ MeV and $P_{11}(M,\Gamma) = (1986 \pm 26^{+10}_{-30}, 296 \pm 100^{+60}_{-10})$ MeV. Other reaction mechanisms have been proposed [39], and more definitive statements will require the measurement of polarization observables.

New results for ΛK^+: Recent measurements of $\gamma p \to \Lambda K^+$ total cross sections from SAPHIR [40] suggest a broad structure around 1900 MeV. An analysis [41] of these and associated differential cross-section and recoil-polarization data suggests the influence of a broad D_{13} state. The fitted resonance parameters are $D_{13}(M, \Gamma) = (1895, 372)$ MeV. The choice of a D_{13} state was based on agreement with quark-model predictions, and further polarization measurements are needed to support this claim.

IV. Non-qqq baryon candidates

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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-$q\overline{q}$ mesons"), there have been suggestions that non-qqq baryons might exist, such as hybrid ($qqqg$) baryons and unstable meson-nucleon bound states [42] (see the "Note on the $\Lambda(1405)$").

If non-qqq states exist, they will be more difficult to verify than hybrid mesons: Hybrid baryons would not have the clean signature of exotic quantum numbers. They should also mix with ordinary qqq states. Their identification will be based on (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 [43,44,45], it may already exist in our Listings. (However, some estimates put the lightest state well above 2 GeV [46].) 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 [43,47] and difficulties with its mass and electromagnetic couplings. If so, this would alter our interpretation of the low-lying P_{11}, P_{13}, P_{31}, and P_{33} resonances [43,48]. In Ref. 48, 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 [49] but were then removed.

Both photoproduction [48,50,51] and electroproduction [51,52] have been considered in the search for a unique hybrid signature. In Ref. 53, 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 $O(1/Q^2)$ 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 ($qqqq\overline{q}$) resonances and H dibaryons ($uuddss$ states). Narrow structures found in proton-nucleus scattering [54] have been attributed to $qqqs\overline{s}$ states, an association based on anomalously large branching fractions to strange-particle channels. The H-dibaryon experiments, while finding possible candidates [55], have generally quoted upper limits [56] for exotic resonance production. Searches for narrow dibaryons in the nucleon-nucleon interactions are also continuing [57].

Finally, there has been a report [58] 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 [59] 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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