N AND Δ RESONANCES

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 $\varDelta$ 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 $N\eta$, $\varLambda K$, and $\varSigma K$ 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 $\varDelta$ 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.

			Status as seen in —						
Particle	$L_{2I\cdot 2J}$	Overall status	$N\pi$	$N\eta$	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.

While no new elastic partial-wave analyses have been published since our last edition, a comprehensive set of resonance parameters has been extracted from a multi-channel analysis of transition amplitudes from πN to eight baryon-meson final states [1]. This work most closely resembles a fit by the Carnegie-Mellon/Berkeley group [2], and has determined both Breit-Wigner and pole parameters for resonances up to about 2 GeV.

The interested reader will find further discussions in the proceedings of two recent conferences [3,4], and in two older reviews [5,6].

II. Using the N and Δ listings

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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 far enough 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 [7,8].

Our Particle Listings and Summary Tables include pole parameters for the N and Δ resonances. However, the Breit-Wigner parameters are most often quoted and are used in model-based studies of the baryons and associated reaction dynamics. Problems associated with this choice were discussed in our 2000 edition [9]. Here we just point out that the use of Breit-Wigner parameters for complicated structures, such as the N(1440), should be avoided. In this case, the method used in Ref. 8 is suitable for the analysis.

In the search for 'missing' quark-model states, indications of new structures occasionally are found. Often these are associated (if possible) with the one- and two-star states listed in Table 1. We caution against this practice: The status of the one- and two-star states found in the Karlsruhe-Helsinki (KH80) [5] and Carnegie-Mellon/Berkeley (CMB80) [10] fits is now doubtful. Predictions for π^+p spin-rotation parameters from those fits are in significant disagreement with recent ITEP/PNPI [11] measurements, whereas the predictions of Ref. 12 are good. This discrepancy has been associated in Ref. 11 with the behavior of a zero trajectory at a 'critical point' (see Sec. 2.1.1 of Ref. 5) near a pion lab momentum of 0.8 GeV/c. According to Ref. 11, the effect on the 4-star resonances $\Delta(1905)$ and $\Delta(1950)$ is small, but the effect on the 3-star resonances $\Delta(1920)$ and $\Delta(1930)$ is large. For a study of the approximation made in Ref. 11 and of problems with some higher resonances, the detailed treatment of zero trajectories in Ref. 13 is relevant. This problem should also be considered in any multi-channel analysis that uses the KH80 and CMB80 amplitudes as input [14].

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 $\pi N \rightarrow \pi N$ 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 [15].

Our Listings omit a number of analyses that are now obsolete. Most of the older results may be found in our 1982 edition [16]. 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. There is an update to the Crawford analysis [17]. 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 $\boldsymbol{\Delta(1232) \to p\gamma}$**:**

Recent determinations of the $E2/M1$ ratio, $(-2.5 \pm 0.1 \pm 0.2)\%$ based on pion photoproduction data [17], $(-1.6 \pm 0.4 \pm 0.2)\%$ based on Compton scattering data [18], and $(-3.07 \pm 0.26 \pm 0.24)\%$ based on both sources of data [19], show considerable scatter around our present estimate of $(-2.5 \pm 0.5)\%$. The electric quadrupole ($E2$) and magnetic dipole ($M1$) amplitudes are related to our helicity amplitudes by

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

A recent MAMI measurement, $(-6.4 \pm 0.7 \pm 0.8)\%$ [20], of the ratio of scalar-quadrupole and magnetic-dipole amplitudes (S_{1+}/M_{1+}) at $\mathrm{Q}^2 = 0.121$ (GeV/c)^2 is in line with Jefferson Lab values at 2.8 and 4.0 (GeV/c)^2. This ratio appears to remain negative and in the 5–15% range up to 4.0 (GeV/c)^2. A discussion of the Q^2 dependence of the $E2/M1$ ratio is given in our 2000 edition [9].

New results for $\boldsymbol{p\eta}$: Fits to η-photoproduction data give $N\gamma$ amplitudes for the $N(1535)$ that are substantially larger than those extracted from fits to π-photoproduction data (see our 1998 Review [21] for details). More recent analyses [22,23] 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. 22 and -2.1 ± 0.2 in Ref. 23. Results inferred from π-photoproduction are about three times 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. A recent quark-model fit [24] demonstrates that a reasonable description is possible with $N(1535)$ and $N(1520)$ couplings consistent with those found from π photoproduction. This work also suggests there may be a third S_{11} state just above the $N(1650)$.

Recent $p(e,e'p)\eta$ cross section measurements [25] have been fitted to extract the $N(1535)$ transition amplitude. Results for $A_{1/2}$ were extracted for values of Q^2 from 0.25 to 1.5 $(\mathrm{GeV}/c)^2$. These smoothly join other Jefferson Lab measurements [26] at Q^2 values of 2.4 and 3.6 $(\mathrm{GeV}/c)^2$.

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 [27] (see the note on “The $\Lambda(1405)$”). If such states exist, they will be more difficult to verify than hybrid mesons. Possibilities are listed in Ref. [28] and in our 2000 edition. No hybrid baryon has yet been clearly established. Other unconventional quark configurations include the H dibaryon (*uuddss*) and the pentaquark ($qqqq\overline{q}$). Recent searches for the H dibaryon at BNL [29,30], KEK [31], and Fermilab [32] have reported null results.

Narrow structures continue to be seen [33] in proton-proton and proton-nucleus scattering. However, a high-precision search for states photo-produced from deuterons has found no structure of statistical significance [34]. A clear understanding of this growing set of experiments remains elusive.

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