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 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 $\pi N \rightarrow N\pi\pi$ 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.

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 and data for πN scattering to six baryon-meson final states [1]. This work 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 [2, 3], and in two older reviews [4, 5].

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.

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, it is also necessary to consider branch points in the lower half plane that belong to thresholds for two-particle final states; see for example Refs. 6 and 7.

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 [8]. 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. 7 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: The status of the one- and two-star states found in the Karlsruhe-Helsinki (KH80) [4] and Carnegie-Mellon/Berkeley (CMB80) [9] fits is now doubtful. Predictions for π^+p spin-rotation parameters from those fits are in significant disagreement with recent ITEP/PNPI measurements [10], whereas the predictions of Ref. 11 are good. This discrepancy has been associated in Ref. 10 with the behavior of a zero trajectory at a "critical point" (see Sec. 2.1.1 of Ref. 4) near a pion lab momentum of 0.8 GeV/c. According to Ref. 10, 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. 10 and of problems with some higher resonances, the detailed treatment of zero trajectories in Ref. 12 is relevant. This problem should also be considered in any multi-channel analysis that uses the KH80 and CMB80 amplitudes as input.

III. Electromagnetic interactions

Revised 2003 by R.L. Workman (George Washington 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 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 [13].

Our Listings omit a number of analyses that are now obsolete. Most of the older results may be found in our 1982 edition [14]. 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 [2]. The errors we give on $N\gamma$ couplings 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 and are discussed in the 2002 *Review* [15].

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

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

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.

See our 2002 *Review* for some further discussion [15].

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, unstable meson-nucleon bound states [16], or pentaquarks ($qqqq\overline{q}$). If hybrid states exist, they will be more difficult to verify than hybrid mesons. Possibilities are listed in Ref. [17] and in our 2000 edition. No hybrid baryon has yet been clearly established. Other unconventional quark configurations include the H dibaryon ($uuddss$). Recent searches for the H dibaryon at BNL [18, 19]. KEK [20], and Fermilab [21] have reported null results.

Recent experiments at a number of labs have reported sharp structures in nK^+ and pK^0 invariant mass distributions, evidence for an S=+1 resonance with a mass of 1540 MeV and a very narrow width (see our note on "A Possible Exotic Baryon Resonance"). This would be a pentaquark candidate. Evidence for a pentaquark state with hidden strangeness ($qqqs\overline{s}$) has also been reported [22].

Narrow structures continue to be seen in proton-proton and proton-nucleus scattering [23]. However, a number of high-precision searches for such states has found no structure of statistical significance [24]. A clear understanding of this growing set of experiments remains elusive.

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