NOTE ON 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 masses, 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 (Sec. II). 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 (Sec. III). Finally, many $N\gamma$ branching fractions have been determined from photoproduction experiments (Sec. IV).

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 uncertainties.

The Baryon Particle Listings give, in addition to the usual Breit-Wigner parameters, the positions and residues of the nearest poles of the resonant partial waves on the second sheet of the complex energy plane. These come from $\pi N \to \pi N$ partial-wave analyses and from a $\pi N \to N\pi\pi$ isobar-model analysis (Sec. III).

The interested reader will find further discussions in two extensive (but now somewhat dated) reviews [1,2] and in the *Proceedings of the 6th International Symposium on Meson-Nucleon Physics and the Structure of the Nucleon* [3].

(References for this Section are at the end of Sec. II.)

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	$L_{2I\,2J}$	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_{311}	****	****						*
$\Delta(2750)$	I_{313}	**	**						
$\Delta(2950)$	K_{315}	**	**						

****	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. Elastic partial-wave analyses and resonance parameters

(by R.L. Workman, Virginia Polytechnic Institute and State University)

A general discussion was given in previous editions [4]. In the following, we only consider new results.

New data: Experimental activity over the past two years has mainly concentrated on the region below 600 MeV [5]. Some of these data remain in preliminary form. The new pionic atom measurement [6] from PSI is particularly interesting as it has updated the πN scattering lengths used in dispersion relations. An experiment at the ITEP accelerator has measured spin-rotation parameters for $\pi^+ p$ elastic scattering at 1.43 GeV/c [7]. The results are surprising, as they strongly contradict predictions from the CMU-Berkeley (CMB) [8] and Karlsruhe-Helsinki (KH) [9]

analyses. More spin-rotation measurements are planned for this energy region.

New Partial-Wave Analyses: The VPI group has updated its resonance parameters [10]. The new determinations are based upon a partial-wave analysis with fixed-t dispersion relation constraints. A search was made for 'small' structures, and two new resonance candidates were found. Discrepancies between this analysis and the CMB [8] and KH [9] analyses still exist.

Batinić *et al.* [11] have used a coupled-channel model to describe the elastic πN amplitudes together with data for $\pi N \to \eta N$. One variant of this model contains two additional (S_{11} and P_{11}) resonances with masses near 1750 MeV. The extra S_{11} resonance is similar to one of the small structures found in the VPI analysis. While there is other circumstantial evidence [12] for this state, further verification is needed.

The Petersburg analysis [13] is now published. The associated preprint was described in the 1992 review. While the published version does not report some of the higher partial waves, the partial-wave solutions are identical.

Resonance Parameters: Höhler has generated pole parameters for the KH solution using the speed-plot method. This study is continuing [14]. Manley [15] has related and compared the pole and Breit-Wigner parameters from the KSU [16], CMB [8], KH [9], and VPI [10] analyses. Good agreement was found for the $\Delta(1232)\,P_{33}$, $N(1520)\,D_{13}$, $N(1650)\,S_{11}$, $N(1675)\,D_{15}$, $N(1680)\,F_{15}$, and $\Delta(1950)\,F_{37}$ pole parameters. The most recent VPI analysis has added a small structure to the high-energy shoulder of the $N(1650)\,S_{11}$. As a result, the associated parameters have changed significantly.

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III. Inelastic two-body and quasi-two-body reactions

(by D.M. Manley, Kent State University)

Since the last edition, no new data nor partial-wave analyses have been published for the inelastic two-body reactions $\pi N \to \Lambda K$ and $\pi N \to \Sigma K$. However, new data *have* been measured and a new analysis published for the $\pi N \to N\eta$ reaction. In particular, an experiment [1] that measured the cross section for $\pi^- p \to n\eta$ from threshold to $p_\pi = 750$ MeV/c ($\sqrt{s} = 1527$ MeV) was recently completed using the AGS at Brookhaven National Laboratory. In addition, the same collaboration also measured the cross section for $K^- p \to \Lambda\eta$. The data from these measurements are currently being analyzed.

A new energy-dependent partial-wave analysis of the reaction $\pi N \to N\eta$ has also been published [2]. The analysis used a coupled three-channel model to describe reactions involving the $N\pi$ and $N\eta$ channels simultaneously. (The third channel was an effective nonphysical two-body $N\pi\pi$ channel.) The eight lowest $I = \frac{1}{2}$ $\pi N \to N\eta$ partial waves were fitted up to a c.m. energy of 2.5 GeV using the πN elastic amplitudes from the Karlsruhe-Helsinki partial-wave analysis [3] as part of the input data base.

Essentially all information on quasi-two-body reactions such as $\pi N \to \Delta\pi$ and $\pi N \to N\rho$ comes from isobar-model analyses of $\pi N \to N\pi\pi$ reactions. Since the last edition, no new analysis of these reactions has been published. A brief review of $\pi N \to N\pi\pi$ analyses can be found in our 1992 edition; for a more recent and extensive review, the interested reader should see [4].

Since the last edition, two new narrow resonance candidates were observed in experiments investigating the diffractive production of hadrons by 70-GeV protons at the SPHINX facility of the IHEP accelerator [5]. In the reaction on carbon nuclei, $p + C \to [\Sigma(1385)^0 K^+] + C$, evidence was found for an $N(2050)$ with mass $M = (2052 \pm 6)$ MeV and width $\Gamma = 35^{+22}_{-35}$ MeV. In the reaction, $p + C \to [\Sigma^0 K^+] + C$, evidence was found for an $N(2000)$ with $M = 1999 \pm 6$ MeV and $\Gamma = 91 \pm 17$ MeV. The small decay widths and large branching ratios for decays involving hyperons make these states candidates for exotic

$qqqs\bar{s}$ baryons. Further evidence suggesting the possible existence of narrow exotic baryons was found by a recent analysis of photographic data obtained during irradiation of the 2-meter hydrogen bubble chamber at CERN by a 16-GeV/c π^- beam [6]. A narrow peak that may be due to the production of a neutral baryon with $M = 3521 \pm 3$ MeV and $\Gamma = 6^{+21}_{-6}$ MeV was observed in the invariant mass spectrum of the $K^0_s K^+ p\pi^-\pi^-$ system.

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IV. Electromagnetic interactions

(by R.L. Crawford, University of Glasgow)

Nearly all the entries in the Listings relating to 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 a large number of partial-wave analyses of single-pion photoproduction, $\gamma N \to \pi N$, on protons and neutrons. The large amount of data has permitted an accurate evaluation of the couplings for many of the resonances with masses below 2 GeV, and has given at least qualitative information about most of the others. Most photoproduction analyses take as input the existence, masses, and widths of the resonances derived from the $\pi N \to \pi N$ analyses, and only determine the $N\gamma$ couplings. In addition to the pion photoproduction analyses, a few couplings have been extracted from η photoproduction and from Compton scattering. 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 parametrization schemes are probably more indicative of the true uncertainties than are the quoted errors.

Probably the most reliable analyses are ARAI 80, CRAWFORD 80, AWAJI 81, FUJII 81, CRAWFORD 83, and ARNDT 96. The Listings include our estimates of the couplings, using the results of these analyses. 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 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

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

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.

The Listings include results of several new analyses of the $N(1535) \to N\gamma$ couplings obtained using recent accurate measurements of the reaction $\gamma N \to N\eta$ near threshold.

Burkert and Elouadrhiri [4] report the result of an analysis of π^0 electroproduction on protons at a virtual photon mass of $Q^2 = -3.2$ (GeV/c)^2 using data from DESY. They evaluated the ratio of electric quadrupole and scalar quadrupole to magnetic dipole amplitudes for the $\Delta(1232)$. Their values,

$$E_{1+}/M_{1+} = 0.06 \pm 0.02 \pm 0.03$$

and

$$S_{1+}/M_{1+} = 0.07 \pm 0.02 \pm 0.03 \;,$$

agree with typical quark model predictions and are qualitatively similar to those obtained from previous analyses for smaller values of $|Q^2|$. They disagree with the predictions from perturbative QCD that $E_{1+}/M_{1+} \to 1$ and $S_{1+}/M_{1+} \to 0$ at large $|Q^2|$.

Mart, Bennhold, and Hyde-Wright [5] apply isobar models developed for $\gamma p \to K^+\Sigma^0$ and $\gamma p \to K^+\Lambda$ to $\gamma p \to K^0\Sigma^+$ and $\gamma n \to K^-\Sigma^+$ and find that they can drastically overpredict the measurements. Including the data for charged Σ production results in drastically reduced values for the Born-term couplings, $g_{K\Sigma N}$ and $g_{K\Lambda N}$, to values well below the SU(3) predictions and values obtained from hadronic processes. The resulting description of the process is resonance dominated. They point out the importance for future analyses of including data for all channels. Their results are not included in the Listings because of the scatter of the values obtained.

Additional information about recent results for the electromagnetic interactions may be found in our 1992 and 1994

editions [1,3]. These include Compton scattering, $K\Lambda$ photoproduction, pion electroproduction, the E2/M1 ratio, and the magnetic moment of the $\Delta(1232)$.

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V. Outlook

(by D.M. Manley, Kent State University)

Much new data related to the study of nucleon resonances will soon come from experiments with electromagnetic probes at CEBAF, which can provide beams of electrons to three experimental halls (A, B, and C) with energies up to 4 GeV. Experiments are now being carried out in Hall C and the commissioning experiments for Hall A are expected to run in mid 1996. The majority of experiments to study nucleon resonances will be carried out in Hall B, which is expected to be completed in late 1996. A very short summary of the experimental program in Hall B can be found in our last edition.

New experiments to study nucleon resonances at European laboratories are already producing interesting results. For example, measurements of total cross sections for the reaction $\gamma p \to p\eta$ at eight c.m. energies between 1487 and 1493 MeV were performed at the ELSA electron facility at Bonn [1] by solely detecting the recoil proton. In addition, very precise measurements of total and differential cross sections for $\gamma p \to p\eta$ from threshold to 1537 MeV (c.m. energy) were performed using the MAMI accelerator in Mainz [2] with the neutral meson spectrometer TAPS. Other facilities are or will be involved in such programs using hadronic beams. For example, two experiments were approved in 1995 to study baryon spectroscopy at the AGS of Brookhaven National Laboratory. The processes, $\pi^- p \to n\eta$, $K^- p \to \Lambda\eta$, and $K^- p \to \Sigma^0\eta$, among others, will be studied by using the Crystal Ball detector (formerly located at SLAC) to identify multiphoton final states [3,4]. As by-products of these investigations, new and improved data also will be obtained for $\pi^- p \to n\pi^0$, and for the inverse photoproduction reactions, $K^- p \to \Lambda\gamma$ and $K^- p \to \Sigma^0\gamma$.

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VI. Non-qqq baryon candidates

The standard quark-model assignments for baryons are outlined in Sec. 12.3 "Baryons: qqq states". As in the meson spectrum (see the "Note on Non-$q\bar{q}$ mesons"), there have been suggestions that some states fall outside this assignment scheme. These include 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 verify than hybrid mesons. Hybrid baryons would not have the clean signature of exotic quantum numbers. They should also mix with ordinary qqq states. The identification of such states will be based 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 the Baryon Particle Listings. (Note, however, that some estimates [5] put the lightest state significantly above 2 GeV.) At present, there are actually not enough known resonances to fill the known multiplets. This is the 'missing resonance' problem. If an existing resonance is identified as a hybrid, we must also account for the expected qqq state.

The Roper resonance, $N(1440)\,P_{11}$, has been considered as a hybrid candidate based upon its quantum numbers [2] 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 [2,6]. In Ref. 6, both the $N(1440)\,P_{11}$ and $\Delta(1600)\,P_{33}$ are hybrid candidates, and the $N(1540)\,P_{13}$ and $\Delta(1550)\,P_{31}$ states are predicted. The P_{13} and P_{31} (1-star) states were listed in the 1990 RPP [7] but were removed from the listings in 1992 [8].

Both photoproduction [6,9,10] and electroproduction [10,11] have been considered in the search for a unique hybrid signature. In Ref. 12, QCD counting rules were used to reveal a characteristic of hybrid electroproduction at high Q^2. If the Roper is a hybrid, its transverse form factor is expected to fall asymptotically $O(1/Q^2)$ faster than a pure qqq state. However,

mixing between qqq and $qqqg$ states will make this identification more difficult.

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

For an extensive review of exotic hadrons, see Landsberg [16].

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