N AND Δ RESONANCES

For a lengthier discussion of N and Δ resonances, see our previous edition, Phys. Rev. **D45**, 1 June 1992, Part II. For Argand plots of the partial-wave amplitudes, see our 1990 edition, Phys. Lett. **B239** (1990).

I. Introduction

(by G. Höhler, University of Karlsruhe and R.L. Workman, Virginia Polytechnic Institute and State University)

The excited states of the nucleon have been studied in a large number of formation and production experiments. The conventional Breit-Wigner 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 made of much smaller sets of data to get some $N\eta$, ΛK, and ΣK branching fractions, and other branching fractions come from isobar-model analyses of $\pi N \to N\pi\pi$ data (Sec. III). Finally, some $N\gamma$ branching fractions have been determined from photoproduction experiments (Sec. IV).

Table 1 lists all the N and Δ entries in the Baryon Full 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 is seen in at least two independent analyses of elastic scattering and if its partial-wave amplitude neither behaves erratically nor has large errors.

The Baryon Full Listings give, in addition to the conventional 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 $\pi N \to N\pi\pi$ isobar-model analyses.

The interested reader will find further discussions in two extensive reviews [1,2], and in the Proceedings of the 5th International Symposium on Meson-Nucleon Physics and the

Structure of the Nucleon [3], and more generally in issues of the πN Newsletter (see the note following Sec. II).

(References for this Section are at the end of Section 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 determination of resonance parameters

(by G. Höhler, University of Karlsruhe and R.L. Workman, Virginia Polytechnic Institute and State University)

Our 1992 edition [4] gave a more general discussion. We here treat only new results.

New data: Most of the experimental activity in the past two years was restricted to the energy range from threshold up to the high side of the $\Delta(1232)$ [5]. There are still discrepancies amongst the new data, and final results of some important measurements are not yet available. These data are of interest for the charge splitting of the $\Delta(1232)$, and they are also of some relevance to other resonances, insofar as dispersion relations used in analyses need input from all momenta.

At higher energies, there have been published spin-rotation data measured at LAMPF [6] and at the Petersburg Nuclear

Physics Institute [7], and also preliminary integrated πp elastic cross sections above 30° and up to 500 MeV from LAMPF [8].

New πN partial-wave analyses: Three new analyses of elastic data have been made since our 1992 edition. Abaev and Kruglov produced a set of single-energy analyses [9] covering from 160 to 600 MeV laboratory kinetic energy. These fits included experimental total inelastic cross sections and constraints on the tails of small amplitudes from the CMB80 [10] and KH80 [11] solutions. Marked deviations from the KH80 S- and P-wave amplitudes were found. The agreement was better with a new solution from Bugg [12], an analysis restricted to the range below 320 MeV.

The VPI group produced a new set of energy-dependent partial-wave analyses [13] with the improvements of including fixed-t dispersion relation constraints for the forward amplitude and for the invariant amplitudes A and B in the range $0 > t > -0.3$ GeV^2. A grid of solutions was produced for different constraint values of pion-nucleon coupling and S-wave scattering lengths. A χ^2 mapping technique was used to determine which of the solutions gave an 'optimal' fit to both the data and the dispersion relation constraints.

Since the KH80 and CMB80 analyses and the new VPI analysis use dispersion relations as constraints, one may ask if it is justified to use these constraints at a time when QCD is assumed to be the theory of strong interactions. The positive answer was given by R. Oehme [14].

Argand plots for the partial wave amplitudes $T(W)$ which show the results of the CMB80 and KH80 analyses may be found in our 1990 edition [15], and tables of the amplitudes are given in [1].

Conventional resonance parameters: The conventional Breit-Wigner parameters were discussed in detail in our 1992 edition [4]. It is important to keep in mind that the width Γ is the value of $\Gamma(W)$ at the resonance energy $W = M$; it depends on the model used for the energy dependence and on the definition of M. The tabulated elasticities and partial widths are similarly model dependent. The model dependence

is the primary reason for the differences in the parameters and their errors quoted by the different groups.

Resonance pole parameters: We add some remarks to the treatment in the previous edition [4]. The resonance pole parameters have the advantage that they are directly related to the definition of a resonance as an unstable intermediate state in a scattering process [16].

Pole parameters for the KH partial wave solutions were determined only recently [17,18]. The method employs not only plots for the speed $|dT/dW|$, which were used in the early seventies, but also Argand plots for dT/dW and fits to the resonance semicircles in the range $M \pm \Gamma/2$ in Argand diagrams for $T(W)$. The parametrization for $T(W)$ agrees with that in [19], but the four parameters of the pole term are treated as constants, since they belong to the pole of $T(W)$. If the background amplitude is elastic, statements made in our 1992 edition [4] concerning the phase of the residue and the elasticity are correct. However, they disagree with the present parametrization in the general case. If the background can be treated as a constant, the model dependence of the pole parameters is weaker than in other methods. This can be assumed for eight of the 4-star resonances [18]. One could try to check if the method proposed in [19] can be applied in practice for a separation of the direct production of inelastic final states and a production by a resonance decay.

For further information on the status of a resonance and on the accuracy of its parameters, there will soon be available a collection of plots [20], calculated from various partial wave analyses.

The parameters of nucleon resonances will remain of interest in the future since they are needed to test various models, such as quark models [21] and Skyrmion models [22]. Finally, they will be needed as soon as these parameters can be calculated from lattice QCD.

References for Section I and II

Note: Many of the references below are to the πN Newsletter, which is edited by G. Höhler, W. Kluge, and B.M.K. Nefkens. Copies may be obtained from W. Kluge, Karlsruhe U. or from B.M.K. Nefkens, UCLA.

1. G. Höhler, *Pion-Nucleon Scattering*, Landolt-Börnstein Vol. **I/9b2** (1983), ed. H. Schopper, Springer Verlag.
2. A.J.G. Hey and R.L. Kelly, Phys. Reports **96**, 71 (1983).
3. *Proceedings of the 5th International Symposium on Pion-Nucleon Physics and the Structure of the Nucleon*, ed. B.M.K. Nefkins and M. Clajus (Boulder, Sep. 1993), published in πN Newsletter No. 8 (1993) and πN Newsletter No. 9 (1994).
4. Review of Particle Properties, Phys. Rev. **D45**, (1 June 1992) Part II.
5. E. Friedman *et al.*, Phys. Lett. **B302**, 18 (1993);
   E. Friedman *et al.*, πN Newsletter No. 8 (1993), p. 11;
   M. Pavan *et al.*, πN Newsletter No. 8 (1993), p. 23;
   C. Joram *et al.*, πN Newsletter No. 8 (1993), p. 30;
   and references given in these papers.
6. I. Supek *et al.*, Phys. Rev. **D47**, 1762 (1993).
7. S.P. Kruglov *et al.*, πN Newsletter No. 8 (1993), p. 42 and references given therein.
8. B.J. Kriss *et al.*, πN Newsletter No. 8 (1993), p. 17.
9. V.V. Abaev and S.P. Kruglov, SPNPI preprint No. 1794, 1992;
   S.P. Kruglov, πN Newsletter No. 8 (1993), p. 42.
10. R.E. Cutkosky *et al.*, Phys. Rev. **D20**, 2804 (1979); and *ibid.* 2839 (1979);
    R.L. Kelly *et al.*, Phys. Rev. **D20**, 2782 (1979); and in *Proceedings of the IVth International Conference on Baryon Resonances* (Toronto, 1980), ed. N. Isgur, p. 19.
11. R. Koch, in *Proceedings of the IVth International Conference on Baryon Resonances* (Toronto, 1980), ed. N. Isgur, p. 3;
    G. Höhler *et al.*, *Handbook of Pion-Nucleon Scattering*, Physics Data 12-1 (1979);
    E. Pietarinen, Nucl. Phys. **B107**, 21 (1976).
12. D.V. Bugg, πN Newsletter No. 6 (1992), p. 7;
    D.V. Bugg, πN Newsletter No. 8 (1993), p. 1.
13. R.A. Arndt, R.L. Workman, and M.M. Pavan, submitted to Phys. Rev. **D**.
14. R. Oehme, πN Newsletter No. 7 (1992), p. 1.

15. Review of Particle Properties, Phys. Lett. **B239** (1990).
16. R.H. Dalitz and R.G. Moorhouse, Proc. Roy. Soc. London **A318**, 279 (1970);
B.H. Bransden and R.G. Moorhouse, *The Pion-Nucleon System* (Princeton Univ. Press, 1973).
17. G. Höhler and A. Schulte, πN Newsletter No. 7 (1992), p. 94.
18. G. Höhler, πN Newsletter No. 9 (1994), p. 1.
19. P.H. Timmers *et al.*, Phys. Rev. **D31**, 99 (1985).
20. G. Höhler, "A Picture Book of Pion-Nucleon Resonances," Karlsruhe preprint TTP93-41, to be published in πN Newsletter.
21. S. Capstick and W. Robert, Phys. Rev. **D47**, 1994 (1993) and CEBAF-TH-93-18.
22. International Workshop on Baryons as Skyrme Solitons, ed. G. Holzwarth (World Scientific, 1993);
B. Schwesinger "Mesonen und Baryonen im Skyrme Modell," Lecture Notes, University of Siegen, Germany, FB Physik.

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

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

Since our 1992 edition, no new data nor partial-wave analyses have been published for the inelastic two-body reactions $\pi N \to N\eta$, $\pi N \to \Lambda K$, and $\pi N \to \Sigma K$. There are recent indications [1] that much of the $\pi N \to N\eta$ data [2] used for the Rutherford partial-wave analysis [3] had poorly determined energies; thus, except for the $N(1535)\,S_{11}$, $N\eta$ branching fractions are omitted from the Baryon Summary Table in this edition. A recent review of these reactions and the quasi-two-body reaction $\pi N \to N\omega$ can be found in Ref. 4.

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, the Kent State multichannel resonance analysis has been published [5]. Although couplings from this analysis were listed in the 1992 edition, the present edition includes new, updated estimates for couplings and branching fractions of many resonances observed in two or more isobar-model analyses. A brief review of $\pi N \to N\pi\pi$ analyses can be found in the 1992 edition; for a more recent and extensive review, the interested reader should see Ref. 6.

Since the last edition, there have been two reports [7,8] of resonances observed in $\pi N \to N4\pi$ reactions. One report [7] of $\pi^- p \to p\pi^+\pi^-\pi^-\pi^0$ data from the CERN liquid-hydrogen bubble chamber gives evidence for an N^* resonance with mass 1700 MeV and width 150 MeV, which decays by the channels $p\eta$, $\Delta 2\pi$, $p3\pi$. The other report [8] of $\pi^+ p \to p\pi^+\pi^+\pi^-\pi^0$ data from the ZhVK-205 liquid-hydrogen bubble chamber (Moscow) gives evidence for an N^* resonance with mass 1780 ± 40 MeV and width 250 ± 80 MeV, which decays by the $p\omega$ channel.

References for Section III

1. M. Clajus and B.M.K. Nefkens, πN Newsletter No. 7 (1992), p. 76.
2. R.M. Brown *et al.*, Nucl. Phys. **B153**, 89 (1979).
3. R.D. Baker *et al.*, Nucl. Phys. **B156**, 93 (1979).

4. D.M. Manley in *New Vistas in Physics with High-Energy Pion Beams*, ed. B.F. Gibson and J.B. McClelland (World Scientific, 1993), p. 119.
5. D.M. Manley and E.M. Saleski, Phys. Rev. **D45**, 4002 (1992).
6. D.M. Manley, πN Newsletter No. 8 (1993), p. 141.
7. Yu.D. Aleshin and V.M. Guzhavin, Sov. J. Nucl. Phys. **55**, 1814 (1992) [Yad. Fiz. **55**, 3255 (1992)].
8. L.Yu. Brovkin *et al.*, Phys. Atom. Nucl. **56**, 762 (1993) [Yad. Fiz. **56**, 90 (1993)].

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 couplings for decay to $N\gamma$. 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 use as input information on 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].

The 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, it is likely that the systematic differences between the analyses caused by using different parametrization schemes are 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, ARNDT 90B, and LI 93. 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 LI 93 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 experimental 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 contain several results for the E2/M1 ratio $(E^{(3)}_{1+}/M^{(3)}_{1+})$ of the $\Delta(1232)$. The analysis of TANABE 85 attempts to distinguish between renormalized and bare couplings; it is, therefore, a model-dependent result and should not be compared directly with the others. Similarly, Christillin and Dillon [3] have made a model-dependent estimate of the ratio. They do not fit directly to data, so their value does not appear in the Listings, but they conclude that the ratio is between zero and -2%. DAVIDSON 90 extracts the K-matrix residues for M_{1+} and E_{1+} using the data from several energy-independent analyses of the $\Delta(1232)$ region. Essentially, they are measuring $\mathrm{Im}(E^{(3)}_{1+})/\mathrm{Im}(M^{(3)}_{1+})$. The value quoted in the Listings is their average over several fits. DAVIDSON 91 uses an effective Lagrangian model to fit to various partial-wave analyses in the $\Delta(1232)$ region.

Christillin and Dillon point out that the spread in predictions may be due to the difference between bare and renormalized couplings. Since the separation of these is essentially model dependent, WORKMAN 92 measures $\mathrm{Im}(E^{(3)}_{1+})/\mathrm{Im}(M^{(3)}_{1+})$ directly from experimental data using the methods of ARNDT 90B. Whereas the other measurements are dependent on rather old partial-wave analyses, WORKMAN 92 uses recent experimental data. They also perform a fit, based on the model of Nozawa *et al.* [4], to extract "bare couplings," and get -3.9%.

The Listings also contain several measurements of the magnetic moment μ_Δ of the $\Delta(1232)^{++}$ from analyses of pion bremsstrahlung, $\pi^+ p \to \gamma\pi^+ p$. NEFKENS 78 is an analysis of UCLA data for pion bremsstrahlung that uses the soft pion model of Pascual and Tarrach [5]. HELLER 87 is a fit to the same data using a nonrelativistic dynamical model that measures the magnetic moment of the "bare" $\Delta(1232)^{++}$. LIN 91B

fits the data of NEFKENS 87 and from SIN [6] with an amplitude that includes the anomalous magnetic moment of the $\Delta(1232)$ and is relativistic, gauge invariant, and consistent with the soft photon theorem. The quantity measured is not identical to the "bare" magnetic moment since it does not take into account the effect of loop contributions. BOSSHARD 91 measured the polarized target asymmetry in pion-proton bremsstrahlung and fit it using the model of HELLER 87. The geometry of the experiment was chosen to maximize the sensitivity to μ_Δ.

See our 1992 edition [1] for brief discussions of Compton scattering, $K\Lambda$ photoproduction, and pion electroproduction.

References for Section IV

1. Particle Data Group, Phys. Rev. **D45**, 1 June 1992, Part II.
2. Particle Data Group, Phys. Lett. **111B** (1982).
3. P. Christillin and G. Dillon, J. Phys. **G15**, 967 (1989).
4. S. Nozawa, P. Blankleider, and T.-S.H. Lee, Nucl. Phys. **A513**, 459 (1990).
5. P. Pascual and R. Tarrach, Nucl. Phys. **B134**, 133 (1978).
6. C.A. Meyer *et al.*, Phys. Rev. **D38**, 754 (1988).

V. Outlook

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

It is anticipated that much new data related to the study of nucleon resonances will come from experiments with electromagnetic probes at CEBAF, which will initially provide beams of electrons and photons with energies up to 4 GeV. Such experiments form the major component of the approved research program for CEBAF's Hall B, which is currently expected to begin operation in Fall, 1996. Other experiments to study nucleon resonances and/or elementary electroproduction or photoproduction reactions will be carried out in CEBAF's Hall A and Hall C, which are expected to being operation in mid-1995 and mid-1994, respectively. The main detector for the Hall-B experiments is the CLAS (CEBAF Large Acceptance Spectrometer), which, with CEBAF's 100% duty cycle, will make possible studies of electroproduction reactions such as $p\,(e,e'\pi^+)n$, $p\,(e,e'p)\pi^0$, $d\,(e,e'\pi^-)pp$, $p\,(e,e'p)\eta$, and $p\,(e,e'p)\omega$, among others. This facility will also use tagged photons to make high-precision measurements of the differential cross section for reactions such as π^0, η, and η' photoproduction. These experiments are expected to improve determinations of the electromagnetic couplings of resonances such as the $\Delta(1232)\,P_{33}$, the $N(1520)\,D_{13}$, the $N(1535)\,S_{11}$, and the $N(1680)\,F_{15}$, which have large photocouplings; they are also expected to provide new information about resonances that couple weakly to the πN channel.

CEBAF is not the only laboratory where new experiments to study nucleon resonances will be carried out. For example, the new Bonn continuous beam machine ELSA will combine two large solid-angle detectors, PHOENICS and SAPHIR, with tagged photon facilities to increase our database from various photoproduction processes [1]. Other facilities are or will be involved in such programs using hadronic beams. For example, plans are underway to study baryon spectroscopy at the Brookhaven National Laboratory AGS [2]. The reactions $\pi^- p \to n\eta$, $K^- p \to \Lambda\eta$, and $K^- p \to \Sigma^0\eta$ will be studied by using the SLAC Crystal Ball to identify multiphoton final states. As by-products of these investigations, new and improved data

also will be obtained for $\pi^- p \to n\pi^0$ and for inverse photoproduction on an unstable target, in particular, $K^- p \to \Lambda\gamma$ and $K^- p \to \Sigma^0\gamma$.

References for Section V

1. D. Menze in "Baryon Spectroscopy and the Structure of the Nucleon," *Proceedings of an International Workshop at Saclay, France 23–25 Sep. 1991*, ed. H.P. Morsch and M. Soyeur (Research Center Conference Service, Jülich, 1992), p. 182.
2. AGS Letter of Intent, "Baryon Spectroscopy with the Crystal Ball," spokespersons B.M.K. Nefkens and R.E. Chrien (Aug. 1993).