Journal of Physics: Conference Series

Status of baryon spectroscopy

To cite this article: D Mark Manley 2005 *J. Phys.: Conf. Ser.* **9** 230

Institute of Physics Publishing Journal of Physics: Conference Series **9** (2005) 230–237
doi:10.1088/1742-6596/9/1/043 First Meeting of the APS Topical Group on Hadronic Physics

Status of baryon spectroscopy

D. Mark Manley

Department of Physics, Kent State University, Kent, OH 44242, USA

E-mail: `manley@kent.edu`

Abstract. Recent experimental progress and existing problems facing baryon spectroscopy are reviewed. Only those baryons containing light quarks (u, d, s) are considered here.

1. Introduction

With the exception of the recently discovered pentaquark candidates, all established baryon resonances can be described as bound states of three quarks. Here the term "established" refers to 3- or 4-star states as classified by the Particle Data Group (PDG) in the *Review of Particle Physics* (RPP) [1]. While meson resonances all belong to SU(3) nonets, baryon resonances have a richer structure since they may be grouped into SU(3) singlets, octets, or decuplets. One of the central questions in baryon spectroscopy is how many effective degrees of freedom are required to describe the full spectrum of baryons. In particular, all observed ordinary 3-quark baryons seem to be describable in terms of a quark-diquark picture. This is to be expected if one views the ground-state nucleon as consisting of three constituent quarks in relative S-wave states, and if the common resonance formation processes (*e.g.*, with pion, kaon, and photon probes) mainly excite single-quark transitions. However, since quantum mechanics leads to configuration mixing, it should be possible (in principle) to excite baryon states that cannot be described as quark-diquark configurations, if they exist. Several of the so-called "missing baryons" have such wave functions.

Table 1 (modified from a table in the "Quark Model" section of the RPP) lists established baryon resonances and their dominant quark-model assignments within a flavor-spin SU(6) basis. Only multiplets having at least two known members are listed. The question marks in this table represent "missing states". The fact that only two decuplet multiplets are listed is because there are many missing Σ^* decuplet states. This table also shows that there are an even larger number of missing Ξ^* states (both octets and decuplets). Among the low-lying missing states, one expects a $3/2^-$ octet with total quark spin $S = 3/2$ belonging to the $(\mathbf{70},1_1^-)$ supermultiplet; however, the only candidate belonging to this supermultiplet is the $N(1700)3/2^-$, which unfortunately is classified as a 3-star state in the RPP although there is little hard evidence for its existence.

The RPP includes a few 1- and 2-star baryons that cannot be easily accommodated by quark models. Examples include the low-lying 1-star state, $\Sigma(1480)$, and the 2-star states, $\Sigma(1560)$ and $\Sigma(1580)3/2^-$. The latter state is of particular interest, because if it exists with the specified quantum numbers, it must be exotic because of its very low mass. It should also have a very narrow width [2]. The Crystal Ball Collaboration recently reported a precise measurement of

Table 1. Quark-model assignments for many of the known baryons in terms of a flavor-spin SU(6) basis. Only the dominant representation is listed. Assignments for some of the states, especially for the $\Lambda(1810)$, $\Lambda(2350)$, $\Xi(1820)$, and $\Xi(2030)$, are merely educated guesses. Note that the $\Sigma(1620)$ and $\Sigma(1880)$ are classified as 2-star states in the RPP.

J^P	(D, L_N^P)	S	Octet members				Singlets
$1/2^+$	$(\mathbf{56},0_0^+)$	1/2	$N(939)$	$\Lambda(1116)$	$\Sigma(1193)$	$\Xi(1318)$	
$1/2^+$	$(\mathbf{56},0_2^+)$	1/2	$N(1440)$	$\Lambda(1600)$	$\Sigma(1660)$	$\Xi(?)$	
$1/2^-$	$(\mathbf{70},1_1^-)$	1/2	$N(1535)$	$\Lambda(1670)$	$\Sigma(1620)$	$\Xi(?)$	$\Lambda(1405)$
$3/2^-$	$(\mathbf{70},1_1^-)$	1/2	$N(1520)$	$\Lambda(1690)$	$\Sigma(1670)$	$\Xi(1820)$	$\Lambda(1520)$
$1/2^-$	$(\mathbf{70},1_1^-)$	3/2	$N(1650)$	$\Lambda(1800)$	$\Sigma(1750)$	$\Xi(?)$	
$5/2^-$	$(\mathbf{70},1_1^-)$	3/2	$N(1675)$	$\Lambda(1830)$	$\Sigma(1775)$	$\Xi(?)$	
$1/2^+$	$(\mathbf{70},0_2^+)$	1/2	$N(1710)$	$\Lambda(1810)$	$\Sigma(1880)$	$\Xi(?)$	$\Lambda(?)$
$3/2^+$	$(\mathbf{56},2_2^+)$	1/2	$N(1720)$	$\Lambda(1890)$	$\Sigma(?)$	$\Xi(?)$	
$5/2^+$	$(\mathbf{56},2_2^+)$	1/2	$N(1680)$	$\Lambda(1820)$	$\Sigma(1915)$	$\Xi(2030)$	
$7/2^-$	$(\mathbf{70},3_3^-)$	1/2	$N(2190)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	$\Lambda(2100)$
$9/2^+$	$(\mathbf{56},4_4^+)$	1/2	$N(2220)$	$\Lambda(2350)$	$\Sigma(?)$	$\Xi(?)$	
			Decuplet members				
$3/2^+$	$(\mathbf{56},0_0^+)$	3/2	$\Delta(1232)$	$\Sigma(1385)$	$\Xi(1520)$	$\Omega(1672)$	
$7/2^+$	$(\mathbf{56},2_2^+)$	3/2	$\Delta(1950)$	$\Sigma(2030)$	$\Xi(?)$	$\Omega(?)$	

$K^- p \to \pi^0 \Lambda$ performed at Brookhaven National Laboratory's AGS [3]. The measurements spanned the c.m. energy range 1565 to 1600 MeV and so allowed a detailed search for the $\Sigma(1580)3/2^-$. No evidence was found for this state or for *any* narrow resonance in the c.m. energy range studied.

2. Problems with quark-model predictions

The literature contains a large number of quark-model predictions for the baryon spectrum. These often describe resonances in terms of harmonic-oscillator basis states. The $N = 0$ oscillator band describes positive-parity ground-state baryons (including the $N(939)$ and $\Delta(1232)$), the $N = 1$ band describes the lowest negative-parity states, the $N = 2$ band describes the first positive-parity excited states, *etc.* Modern large-basis calculations are generally successful in describing the pattern of experimental states within a harmonic-oscillator band, but a common problem seems to be that the center of gravity of the $N = 1$ band is predicted to be too low and that of the $N = 2$ band is predicted to be too high. For example, the relativized quark model of Capstick and Isgur [4] predicts the center of gravity of the $N = 1$ band to be about 50 MeV too low and the center of gravity of the $N = 2$ band to be about 40 MeV too high. This well-known model includes a hyperfine interaction deduced from single-gluon exchange. A similar effect occurs in the semirelativistic constituent-quark model with linear confinement and a hyperfine interaction deduced from Goldstone-boson exchange [5].

Another well-known problem with many quark-model predictions is the "spin-orbit puzzle". Experimentally there seems to be little evidence for a strong spin-orbit interaction between the constituent quarks in a baryon as predicted, for example, by single-gluon exchange. This is evident from Table 1. For example, the $S = 1/2$ states, $N(1535)1/2^-$ and $N(1520)3/2^-$, appear nearly degenerate, as do the $S = 3/2$ states, $N(1650)1/2^-$, $N(1700)3/2^-$, and $N(1675)5/2^-$. Similarly, the $S = 1/2$ states, $\Lambda(1670)1/2^-$ and $\Lambda(1690)3/2^-$, appear nearly degenerate. (Here, S denotes the total intrinsic spin of the constituent quarks.) By contrast, the singlet $S = 1/2$

states, $\Lambda(1405)1/2^-$ and $\Lambda(1520)3/2^-$, are split by more than 100 MeV. Capstick and Isgur have reported [4] that this problem is simply a flaw of nonrelativistic quark models. In particular, they claim that the spin-orbit interaction arising from single-gluon exchange is nearly cancelled by a relativistic spin-orbit term arising from the adiabatic potential via Thomas precession. While that might be the case, it seems that no model is yet able to describe adequately the experimental pattern of all baryon spin-orbit multiplets (to the best knowledge of this author).

3. Recent developments

3.1. E2/M1 ratio for Δ(1232)

The $\Delta(1232)$ is the lowest example of a "stretched-state" baryon – one in which its total spin is given by $J = L+S = L+3/2$, where L is the total orbital angular momentum of the constituent quarks and $S = 3/2$ is their total intrinsic spin. In the absence of configuration-mixing effects, the E/M ratio for such states is predicted to vanish. Nonzero ratios provide information about these configuration-mixing effects, which may be considered to arise for example from color hyperfine interactions – or to deformation of the baryon. The best studied example is the $\Delta(1232)$. The latest PDG estimate [1] for this ratio is $E2/M1 = -0.025 \pm 0.005$. In 2001, the Partial-Wave Analysis Working Group of BRAG (the Baryon Resonance Analysis Group) reported [6] on a series of fits by several different groups to low-energy (180-450 MeV) and medium-energy (180-1200 MeV) benchmark datasets. Results of these fits were compared to gauge the model dependence of such fits, given identical data and a single method for handling uncertainties. From the combined set of benchmark fits, the ratio was found to be $E2/M1 = -0.0238 \pm 0.0027$. The important quantity here is the uncertainty, since different fitted datasets could shift the central value.

Oddly, no attention seems to have been given to other stretched-state baryons, such as $N(1675)5/2^-$ or $\Delta(1950)7/2^+$. The electric and magnetic multipole amplitudes for stretched-state baryons can be related to the helicity amplitudes by a rotation [7]:

$$M = -\sqrt{\frac{\ell}{2(\ell+1)}}A_{1/2} - \sqrt{\frac{\ell+2}{2(\ell+1)}}A_{3/2} \,, \tag{1}$$

$$E = -\sqrt{\frac{\ell+2}{2(\ell+1)}}A_{1/2} + \sqrt{\frac{\ell}{2(\ell+1)}}A_{3/2} \,, \tag{2}$$

where ℓ is the orbital angular momentum quantum number for exciting the resonance in πN scattering. (*I.e.*, $\ell = 1$ for $\Delta(1232)3/2^+$, $\ell = 2$ for $N(1675)5/2^-$, *etc.*) Thus, if we assume that the E/M ratio is zero, then we may predict ratios for the photodecay helicity amplitudes, as given in Table 2. The difference between the experimental (PDG) ratios and the predicted helicity-amplitude ratios is attributed to nonzero E/M ratios. In particular, the numbers in Table 2 imply that $E2/M1$ is about -0.025 for $\Delta(1232)3/2^-$, that $E3/M2$ is about $+0.02$ for $N(1675)5/2^-$, and that $E4/M3$ is consistent with zero for $\Delta(1950)7/2^+$.

3.2. Properties of $N(1535)1/2^-$

The $N(1535)1/2^-$ (or $S_{11}(1535)$) resonance is unique among nucleon resonances as being the only state having a large decay branch to ηN. This S-wave state produces a rapid rise in the cross sections for $\pi^- p \to \eta n$ and $\gamma p \to \eta p$ just above the ηN threshold. The γp helicity amplitude for $N(1535)1/2^-$ was determined to be $A_{1/2} = 0.060 \pm 0.015$ GeV$^{-1/2}$ in the SM95 solution of the partial-wave analysis of single-pion photoproduction by Arndt *et al.* [8]. Other groups analyzing single-pion photoproducton obtained similar results [1]. Then in 1995, Krusche *et al.*

Table 2. PDG estimates for photodecay helicity amplitudes for three baryon stretched states. Ratios based on PDG estimates of the helicity amplitudes are compared with predicted ratios, which were calculated based on the assumption that the corresponding E/M ratios are zero. (For $N(1675)5/2^-$, only the γn amplitudes and ratio are given since the corresponding γp amplitudes are small and poorly determined.)

	PDG Estimates			Predicted Ratio
Resonance	$A_{3/2}$ (GeV$^{-1/2}$)	$A_{1/2}$ (GeV$^{-1/2}$)	$A_{3/2}/A_{1/2}$	$A_{3/2}/A_{1/2}$
$\Delta(1232)3/2^+$	$-0.250(8)$	$-0.135(6)$	1.85	$\sqrt{3} = 1.73$
$N(1675)5/2^-$	$-0.058(13)$	$-0.043(12)$	1.35	$\sqrt{2} = 1.41$
$\Delta(1950)7/2^+$	$-0.097(10)$	$-0.076(12)$	1.28	$\sqrt{5/3} = 1.29$

[9] published first results of precise total and differential cross sections for $\gamma p \to \eta p$ measured at MAMI. An analysis of these η photoproduction measurements surprised the hadron physics community by producing a γp amplitude of $A_{1/2} = 0.125 \pm 0.025$ GeV$^{-1/2}$ – a value *double* that obtained from the pion photoproduction experiments. An analysis two years later [10] led to the result, $A_{1/2} = 0.120 \pm 0.011 \pm 0.015$ GeV$^{-1/2}$. The most recent PDG estimate for this amplitude is $A_{1/2} = 0.090 \pm 0.030$ GeV$^{-1/2}$ [1]. What these results illustrate is the importance of using coupled-channel partial-wave analyses to obtain consistent results.

One of the problems that has long plagued the determination of precise parameters for the $N(1535)1/2^-$ resonance has been an absence of precise cross sections for $\pi^- p \to \eta n$. Figure 1 shows the results of new measurements performed by the Crystal Ball Collaboration at Brookhaven National Laboratory's AGS [11]. These results will hopefully lead to better determined parameters for the $N(1535)1/2^-$.

3.3. Exclusive photoproduction of Cascade hyperons

As noted in the Introduction, little is known experimentally about the doubly strange Cascade (Ξ) hyperons. Past studies of these states have centered on their production with K^- beams. Fermilab is the only known facility where K^- beams might be available for future studies of Ξ production [12], but baryon spectroscopy has traditionally not been considered part of Fermilab's high-energy physics mission. An alternative method of producing Ξ resonances is to use photoproduction reactions. Two groups have studied the inclusive process $\gamma p \to \Xi^- X$ [13, 14] and, recently, the CLAS Collaboration at JLab reported the first measurement of the exclusive process $\gamma p \to K^+ K^+ \Xi^-$ for $3.2 < E_\gamma < 3.9$ GeV [15]. The missing mass in the process $\gamma p \to K^+ K^+ X$ was used to measure the cross section for the ground state $\Xi^-(1321)1/2^+$, and to establish a signal for the first excited state, $\Xi^-(1530)3/2^+$. (See Fig. 2.) While the measurement itself was limited by statistics, the method clearly demonstrates the viability of using this technique for future searches of high-mass Ξ^* states.

3.4. Baryon mass spectrum from lattice QCD

Lattice QCD calculations for baryon ground states are now able to reproduce experimental masses to within about 5-10%. Recently several papers have been published which use lattice QCD calculations to study the lowest-lying baryon excited states with spin $J = 1/2$. These are experimentally the $N(1440)1/2^+$ (or Roper resonance) and the $N(1535)1/2^-$. The experimental observation that the Roper resonance lies lower in mass than the first negative-parity baryon is an old puzzle in baryon spectroscopy. Various authors have suggested that the Roper resonance might not be an ordinary three-quark state. Instead, the Roper resonance has been suggested

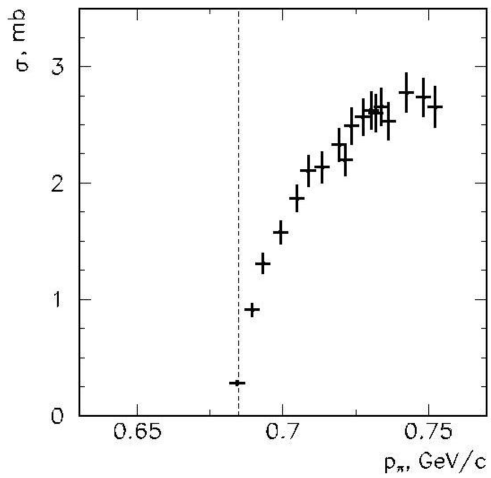

Figure 1. Total cross section for $\pi^- p \to \eta n$ based on $\eta \to 2\gamma$ decay. The dashed line indicates the η production threshold at laboratory momentum $p_\pi = 685$ MeV/c. (Figure taken from Ref. [11], reproduced with permission of the author.)

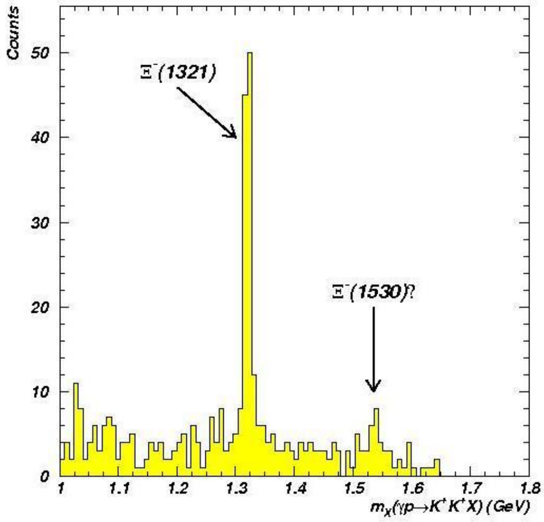

Figure 2. The missing mass m_X in the process $p(\gamma, K^+K^+)X$ for the *g6a* data set. The figure has not been corrected for acceptance. The ground state $\Xi^-(1320)1/2^+$ is clearly seen; the signal-to-background ratio exceeds 10:1. A possible enhancement is seen in the plot at the position of the first excited state $\Xi^-(1530)3/2^+$. The arrow indicates the RPP mass of this state at 1.535 GeV. (Figure taken from Ref. [15], reproduced with permission of the author.)

to be alternatively (i) a threshold effect associated with opening of the $\Delta\pi$ channel, (ii) a hybrid baryon (a state with explicit gluon excitations), and recently, (iii) a pentaquark. Quark potential models have been unable to explain fully the low mass of Roper resonance, and such calculations generally get the wrong sign for its photodecay amplitudes. The question of whether the Roper resonance is an ordinary 3-quark state or something more exotic requires lattice QCD for an answer.

Recently, Lee and collaborators [16, 17] and Sasaki [18] reported lattice calculations that show a level switching between the lowest $1/2^-$ N^* nucleon and the corresponding $1/2^+$ N' state identified with the Roper resonance. This level switching occurs where the lightest pion mass achieved on the lattice is close to the physical pion mass. (See Fig. 3.) Sasaki [18] claims that the level switching between the N^* state and the Roper state should happen in lattice simulations with large spatial size which is larger than 3.0 fm. Preliminary results by both Lee and Sasaki indicate that the Roper resonance shows up naturally on the lattice as the first 3-quark excited state of the nucleon.

3.5. Missing resonances

One of the main goals of the Hall B facility at JLab is to find evidence for the "missing resonances". As mentioned in the Introduction, these are states predicted by quark models but not observed experimentally. Essentially all baryon resonances were discovered in experiments involving pion or kaon probes. The fact that the "missing resonances" were not seen in such

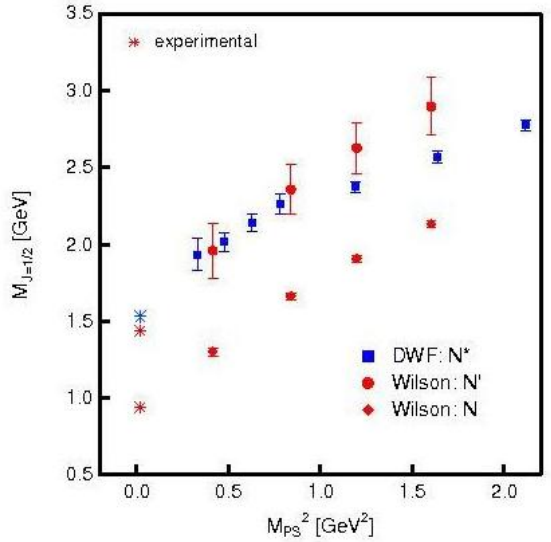

Figure 3. Masses of the ground state (diamond) and the radial excited state (circle) of the nucleon in the infinite volume as a function of pseudo pion mass squared. For comparison, masses of the negative-parity nucleon (square) from Ref. [19] are also plotted. (Figure taken from Ref. [18], reproduced with permission of the author.)

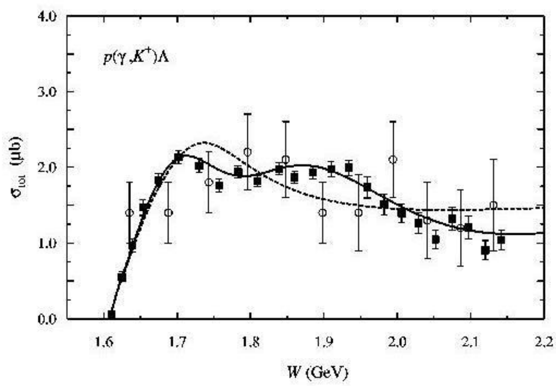

Figure 4. Total cross section for $K^+\Lambda$ photoproduction on the proton. The dashed line shows the model without the $D_{13}(1960)$ resonance, while the solid line is obtained by including the $D_{13}(1960)$ state. The new SAPHIR data [20] are denoted by the solid squares, old data [21] are shown by open circles. (Figure taken from Ref. [22].) Reprinted FIG. 1 from T. Mart and C. Bennhold, *Phys. Rev. C* 61, 012201-1 (1999). Copyright (1999) by the American Physical Society.

experiments may indicate either that they don't exist or simply that they couple only weakly to pions and kaons. For this reason, it makes sense to look for them with other probes, such as real and virtual photons.

In 1998, measurements of total and differential cross sections for $\gamma p \to K^+\Lambda$ and $\gamma p \to K^+\Sigma^0$ at Bonn's electron stretcher ring ELSA were reported by the SAPHIR Collaboration [20]. These measurements show an intriging "missing resonance" structure at a total c.m. energy of about 1900 MeV. The following year, Mart and Bennhold [22] reported an investigation of this feature with an isobar model. (See Fig. 4.) They concluded that the structure could be well explained as a new D_{13} resonance at 1895 MeV. Since then, other authors have indicated that the structure might instead be a P_{13} resonance, or involve contributions from more than one state, such as a D_{15} resonance. In any case, the measurements generated much excitement and controversy in the hadronic physics community, and provided perhaps the first evidence for a "missing baryon".

In 2003, the CLAS Collaboration reported measurements of the $ep \to e'p\pi^+\pi^-$ reaction [23]. The experiment was performed at JLab in 1999 using the CEBAF Large Acceptance Spectrometer (CLAS). The data were analyzed using a phenomenological calculation incorporating the available information on the N^* and Δ resonances in the 1.2–2 GeV mass range. Discrepancies between the data around 1.7 GeV and the calculation were observed, so further analysis was carried out by allowing the resonance parameters to vary in a number of ways. (See Fig. 5.) The best fit corresponded to a prominent wave with $J^P = 3/2^+$ (its isospin is indeterminate). This state could be attributed to the established $N(1720)3/2^+$ state, but with parameters significantly modified from its PDG values, or it could correspond to a new baryon state. This new state, if it exists, would have a rather narrow width, a strong $\Delta\pi$ coupling, and a small ρN coupling.

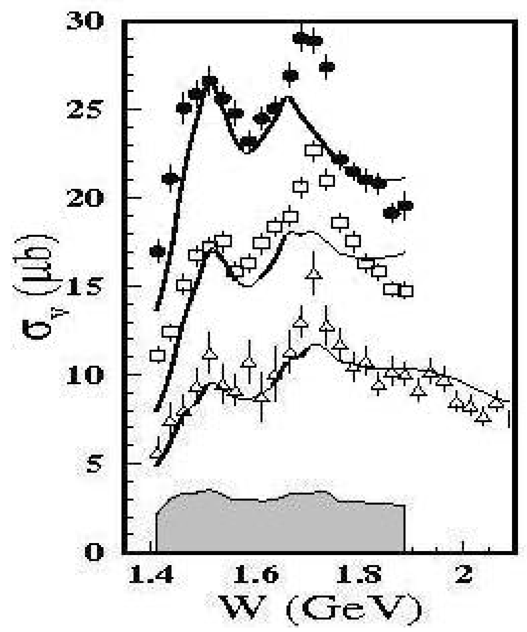

Figure 5. Total cross section for $\gamma_v p \rightarrow p\pi^+\pi^-$ as a function of W. Data from CLAS are shown at Q^2 = 0.5–0.8 (GeV/c)^2 (full points), Q^2 = 0.8–1.1 (GeV/c)^2 (open squares), and Q^2 = 1.1–1.5 (GeV/c)^2 (open triangles). Error bars are statistical only, while the bottom band shows the systematic error for the lowest Q^2 bin. (Figure taken from Ref. [23].) Reprinted FIG. 1 with permission from M. Ripani *et al.* (CLAS Collaboration), *Phys. Rev. Lett.*, 022002-3 (2003). Copyright (2003) by the American Physical Society.

4. Summary

The field of baryon spectroscopy is undergoing a remarkable surge of high-precision new data from a number of laboratories, including JLab, Mainz, Graal, BES, and BNL. Electromagnetic facilities are providing most of the new data, but high-precision hadronic data are also necessary to interpret the data fully. The consensus seems to be that multichannel partial-wave analyses provide a promising method to analyze these data if we insist on consistent results for resonance properties in different reactions. Spin observables are very valuable in such analyses as they provide additional constraints on the solutions.

The basic goal of studying baryon structure is to obtain a better understanding of quark confinement and QCD in the nonperturbative regime. While the recent news about the possible discovery of pentaquarks was perhaps the most exciting development in baryon spectroscopy ever, the final interpretation of the "pentaquark data" is still an open question. Since it is unlikely that lattice QCD will soon provide the detailed information about excited baryons which is desired, the experimental search for missing resonances, hybrids, and pentaquarks must continue.

Acknowledgments

The author thanks the organizers of GHP2004 for their hospitality and their invitation to speak at the conference. The technical assistance of Kent State graduate students, John Tulpan and Hongyu Zhang, is much appreciated. This work was supported in part by DOE Grant No. DE-FG02-01ER41194.

References

[1] Eidelman *et al.* 2004 *Phys. Lett.* B **592** 1-1110
[2] Litchfield P J 1974 *Phys. Lett.* B **51** 509-11
[3] Olmsted J *et al.* 2004 *Phys. Lett.* B **588** 29-34
[4] Capstick S and Isgur N 1986 *Phys. Rev.* D **34** 2809-35
[5] Wagenbrunn I, Glozman L Ya, Plessas W, and Varga K 1999 *Few-Body Systems Suppl.* **11** 25-8
[6] Arndt R A *et al.* 2001 *NSTAR 2001: Proc. Wksp. on the Physics of Excited Nucleons*, ed D Drechsel and L Tiator (World Scientific) pp 467-92

[7] Manley D M 1998 *Proc. GW/JLab Wksp. on N^* Physics*, ed D Drechsel, G Höhler, W Kluge, H Leutwyler, B M K Nefkens, and H-M Staudenmaier, πN Newsletter No. 14 pp 158-67
[8] Arndt R A, Strakovsky I I, and Workman R L 1996 *Phys. Rev.* C **53** 430-40
[9] Krusche B *et al.* 1995 *Phys. Rev. Lett.* **74** 3736-9
[10] Krusche B, Mukhopadhyay N C, Zhang J-F, and Benmerrouche M 1997 *Phys. Lett.* B **397** 171-6
[11] Starostin A *et al.* 2004 (submitted to Phys. Rev. C)
[12] Raja R 2004 (private communication)
[13] Alston D *et al.* 1982 *Nucl. Phys.* B **198** 189
[14] Abe K *et al.* 1985 *Phys. Rev.* D **32** 2869-82
[15] Price J *et al.* 2004 arXiv:nucl-ex/0409030
[16] Lee F X 2002 *NSTAR 2002: Proc. Wksp. on the Physics of Excited Nucleons*, ed S A Dytman and E S Swanson (World Scientific) pp 320-4
[17] Mathur N, Chen Y, Dong S J, Draper T, Horvath I, Lee F X, Liu K F, and Zhang J B 2004 arXiv:hep-ph/0306199
[18] Sasaki S 2003 *Prog. Theor. Phys. Suppl.* **151** 143
[19] Sasaki S, Blum T, and Ohta S 2002 *Phys. Rev.* D **65** 074503
[20] Tran M Q *et al.* 1998 *Phys. Lett.* B **445** 20-6
[21] Erbe R *et al.* 1969 *Phys. Rev.* **188** 2060-77
[22] Mart T and Bennhold C 1999 *Phys. Rev.* C **61** 012201
[23] Ripani M *et al.* 2003 *Phys. Rev. Lett.* **91** 022002