PHYSICAL REVIEW D VOLUME 57, NUMBER 7 1 APRIL 1998

New baryons in the $\Delta\eta$ and $\Delta\omega$ channels

Simon Capstick
Supercomputer Computations Research Institute and Department of Physics, Florida State University, Tallahassee, Florida 32306

W. Roberts
Department of Physics, Old Dominion University, Norfolk, Virginia 23529
and Thomas Jefferson National Accelerator Facility, 12000 Jefferson Avenue, Newport News, Virginia 23606

(Received 28 August 1997; revised manuscript received 9 January 1998; published 3 March 1998)

The decays of excited nonstrange baryons into the final states $\Delta\eta$ and $\Delta\omega$ are examined in a relativized quark pair creation model. The wave functions and parameters of the model are fixed by previous calculations of $N\pi$ and $N\pi\pi$, etc., decays through various quasi-two-body channels including $N\eta$ and $N\omega$. Our results show that the combination of thresholds just below the region of interest and the isospin selectivity of these channels should allow the confirmation of several weakly established Δ baryons and the discovery of new Δ baryons in pion and photoproduction of these final states. [S0556-2821(98)01609-9]

PACS number(s): 13.30.Eg, 12.39.−x, 14.20.Gk

I. INTRODUCTION

Quark models of baryon structure based on three effective quark degrees of freedom predict the existence of more states than have previously been seen in analyses of $N\pi$ elastic scattering. In particular, there are approximately nine ‘‘missing’’ states predicted by quark potential models to lie in the first band of positive-parity excited states (which we define as states whose wave functions are predominantly $N=2$ band when expanded in a harmonic oscillator basis). One of these states, a second $N\frac{3}{2}^+$ (P_{13}) resonance, may have been discovered in the coupled channel analysis of Manley and Saleski [1]. There remain six missing nucleon and two missing Δ states with model masses between approximately 1850 and 2050 MeV. There are also many undiscovered states predicted by these models which have wave functions which lie predominantly in the $N=3$ and higher bands, the lightest of which are predicted to have negative parity [2,3].

Models of this kind, when combined with a model of the strong decays of baryon states [4], yield a simple explanation for the absence of the missing states [5–8] in analyses of $N\pi$ elastic scattering—they simply have weak $N\pi$ couplings and so contribute little to $N\pi$ scattering amplitudes in their partial waves. A simple solution is to produce these states electromagnetically with real photons or by electron scattering, and then look for their decays to final states other than $N\pi$ [9]. As part of the N^* program in Hall B at the Thomas Jefferson National Accelerator Facility (TJNAF), an experiment [10] will study $\gamma p\to p\pi^+\pi^-$, with analysis focusing on $\gamma p\to\Delta^{++}\pi^-$, $\gamma p\to\Delta^0\pi^+$ and $\gamma p\to p\rho^0$. Previous theoretical work [5,6,11,8] has shown that several of the missing states and many of the undiscovered states have sizeable couplings to these channels. Other experiments will focus on the decays of such states to $N\eta$ [12], $N\eta$ and $N\eta'$ [13], and $N\omega$ [14]. These channels offer the advantage of being isospin selective, in that only $I=\frac{1}{2}\,N^*$ resonances (as opposed to $I=\frac{3}{2}\Delta^*$ resonances) can couple to these final states. Given the predicted near degeneracy of broad states in several partial waves in this region, this isospin selectivity should simplify what is likely to be a difficult analysis to extract information about these states.

Detection and analysis of the final states $\Delta(1232)\eta$ and $\Delta\omega$ in electromagnetic production from protons at TJNAF will be complicated by the increased particle multiplicity, and by the presence of an additional neutral particle in the final state resulting from the decays $\Delta^+\to p\pi^0$, $n\pi^+$. For these experiments, it may be better to produce these final states from the neutron in the deuteron [15], reconstruct the $\Delta^0\to p\pi^+$ charged particle decay, and use missing mass to identify the η or ω. At the BNL Alternating Gradient Synchrotron (AGS), the properties of the Crystal Ball detector make it ideal for examining the process $\pi^-p\to n\pi^0\eta$. The final state in $\pi^+p\to p\pi^+\eta$ is more difficult to detect but can, in principle, also be seen using the Crystal Ball [16]. Despite these detection difficulties, these channels also have the advantage of being isospin selective, and can in principle isolate the two missing Δ resonances and higher lying Δ states if they are present and are produced.

Another advantage of a $\Delta\eta$ experiment is that the threshold for this reaction lies just below the mass region where these states are predicted. The nominal $\Delta\eta$ threshold is at 1780 MeV; as we integrate over the lineshape of the Δ, the effective threshold is at $m_N+m_\pi+m_\eta\simeq1630$ MeV. This is to be compared to mass predictions [2,3] for the lightest missing states of around 1800–1850 MeV for $[\Delta\frac{1}{2}^+]_1$ and around 1950–2000 MeV for $[\Delta\frac{3}{2}^+]_4$ (which would be a first P_{31} and a fourth P_{33} state in $N\pi$, respectively). It is generally true (in decay models and in experiment) that once the energy available for a decay increases beyond the region where the phase space has initially become appreciable, the decay amplitudes tend to decrease rapidly as the three momentum available to the final particles increases and the wave function overlaps diminish.

Here we provide predictions for the decay amplitudes into the final states $\Delta\eta$ and $\Delta\omega$ of all states (missing and seen in $N\pi$) with wave functions predominantly in the $N=1$ and $N=2$ bands, and also for several low-lying states in higher bands, using the relativized model of baryon decays based on the ${}^3P_0$ pair creation model of Refs. [7] and [11]. Decays into the $\Delta\eta$ channel have been previously considered by Bijker, Iachello and Leviatan in Ref. [8], within an algebraic model of the spectrum and wave functions, using pointlike emitted mesons.

In the present calculation model parameters are taken from our previous work and not adjusted. Wave functions are taken from the relativized model of Ref. [3], which describes all of the states considered here in a consistent picture. In order to be in accord with the Particle Data Group (PDG) [17] conventional definitions of decay widths, we have determined the decay momentum using the central value of the PDG quoted mass for resonances seen in $N\pi$, and the predicted mass from Ref. [3] for missing and undiscovered states. We have also integrated over the lineshape of the final Δ baryon, with the final phase space as prescribed in the meson decay calculation of Ref. [18]; for details of this procedure see Eq. (8) of Ref. [11] (note that we do not integrate over the narrow [8 MeV width] ω line shape). As a consequence there are states below the nominal thresholds which have non-zero decay amplitudes.

In keeping with the convention of Ref. [11], the phases of the amplitudes are determined as follows. We quote the product $A^{X\dagger}_{\Delta M}A^{X}_{N\pi}/|A^{X}_{N\pi}|$ of the predicted decay amplitude for $X\rightarrow\Delta M$ (where M is either η or ω) and the phase of the decay amplitude for $X\rightarrow N\pi$, the latter being unobservable in $N\pi$ elastic scattering (note factors of $+i$, conventionally suppressed in quoting amplitudes for decays of negative parity baryons to NM or $N\gamma$, where M has negative parity, do not affect this product). This eliminates problems with (unphysical) sign conventions for wave functions, and the relative signs of these products are then predictions for the (physically significant) relative phases of the contributions of states X in the process $N\pi\rightarrow X\rightarrow\Delta M$. Since the missing and undiscovered states may have small $N\pi$ couplings it may be useful to find the relative signs of the contributions of states X in the process $N\gamma\rightarrow X\rightarrow\Delta\eta$. As the photocouplings of Ref. [19] are also quoted inclusive of the $N\pi$ sign, $A^{X\dagger}_{N\gamma}A^{X}_{N\pi}/|A^{X}_{N\pi}|$, then simply multiplying the quoted photocouplings by the amplitudes quoted here will yield the relative phases of the contributions of states X in $N\gamma\rightarrow X\rightarrow\Delta M$.

We note that we have chosen the meson wave flavor functions as

$$\eta=\frac{1}{\sqrt{2}}\left[\frac{1}{\sqrt{2}}(u\bar{u}+d\bar{d})-s\bar{s}\right],$$

$$\eta'=\frac{1}{\sqrt{2}}\left[\frac{1}{\sqrt{2}}(u\bar{u}+d\bar{d})+s\bar{s}\right], \tag{1}$$

$$\omega=\frac{1}{\sqrt{2}}(u\bar{u}+d\bar{d}),$$

i.e., we allow for ideal mixing between ω and $\phi=s\bar{s}$, and an η-η' mixing angle of $\theta_P=-9.7°$.

II. RESULTS AND DISCUSSION

Our results are given in Tables I to IV, where we list the model state, its assignment (if any) to a resonance from the analyses, and its decay amplitudes into the $\Delta\eta$ and $\Delta\omega$ channels. The predictions for the $N\pi$ decay amplitudes for each state [7] and values for these amplitudes extracted from the PDG [17] are also included for ease of identification of missing resonances. All theoretical amplitudes are given with upper and lower limits, along with the central value, in order to convey the uncertainty in our results due to the uncertainty in the resonance's mass. These correspond to our predictions for the amplitudes for a resonance whose mass is set to the upper and lower limits, and to the central value, of the experimentally determined mass. For states as yet unseen in the analyses of the data, we have adopted a ''standard'' uncertainty in the mass of 150 MeV and used the model predictions for the state's mass for the central value. If a state below the effective threshold has been omitted from a table it is because our predictions for all of its amplitudes are zero.

For completeness we have also calculated decays to the $\Delta\eta'$ channel, and find that all of the amplitudes for the states considered here are small. This is primarily due to the high effective (nominal) threshold of roughly 2040 (2190) MeV. We do not record these amplitudes here, but we comment further on this channel in our conclusions.

Figures 1 to 4 show the predictions of the model of Ref. [3] for the masses of excited Δ states below 2200 MeV, along with our predictions for the square roots of the initial channel partial width and the final channel partial width for each state for the reactions $\pi N\rightarrow X\rightarrow\Delta\eta$, $\gamma N\rightarrow X\rightarrow\Delta\eta$, $\pi N\rightarrow X\rightarrow\Delta\omega$, and $\gamma N\rightarrow X\rightarrow\Delta\omega$. Photon partial widths are calculated using the results of Ref. [19]. When the energy of the initial state in the center of momentum frame coincides with the mass of a given resonance, the strength of the contribution of that resonance will be proportional to the product of the initial and final channel partial widths. We can estimate which states should contribute strongly in a given energy region by comparing the products of our predictions for the square roots of the initial and final channel partial widths of states in that region. Model states in the figures which have well established (three or four stars [17]) counterparts from the analyses are distinguished from those which do not, in order to make it simple to assess which new states may be seen in experiments of this kind.

A. $\Delta\eta$ decays

The results for this decay channel are shown in Tables I and II, and our predictions for the relative contributions of model states below 2200 MeV to pion production of the $\Delta\eta$ final state are illustrated in Fig. 1, and to photoproduction in Fig. 2.

In Fig. 1 we see that the process $N\pi\rightarrow\Delta\eta$ is likely to get its largest contributions from several positive-parity excited Δ baryons in the region 1850–2000 MeV. The $\Delta\eta$ decay amplitudes for lighter states are predictably small due to the effective (nominal) threshold of 1638 (1780) MeV, and at higher energies the $N\pi$ amplitudes start to fall off. If, in addition to differential and total cross sections, we assume that high-quality data for polarization observables become available, this would make possible isolation of the different partial waves. Figure 1 shows that with such an analysis it is likely that the weak first P_{31} state $\Delta(1740)$ seen in the multichannel analysis of Ref. [1] could be confirmed, as it

TABLE I. Results for Δ states in the $N=1$ and $N=2$ bands in the $\Delta\eta$ channel. $N\pi$ amplitudes from Ref. [7] are included to explain our assignments of the model states to resonances. Notation for model states is $[J^P]_n$ (mass [MeV]), where J^P is the spin-parity of the state and n its principal quantum number. The first row gives our model results, while the second row lists the $N\pi$ amplitudes from the partial-wave analyses, as well as the Particle Data Group (PDG) name for the state, its $N\pi$ partial wave, and its PDG star rating. Light states with zero amplitudes are omitted from the table.

Model state $N\pi$ state/rating	$N\pi$	$\Delta\eta$	$\Delta\eta$	$\sqrt{\Gamma^{\rm tot}_{\Delta\eta}}$
		s	d	
$[\Delta\,\frac{3}{2}^-]_1(1620)$	4.9 ± 0.7	$1.1^{+3.2}_{-1.1}$	$0.0^{+0.3}_{-0.0}$	$1.1^{+3.2}_{-1.1}$
$\Delta(1700)D_{33}$****	6.5 ± 2.0			
		p		
$[\Delta\,\frac{1}{2}^+]_1(1835)$	$3.9^{+0.4}_{-0.7}$	$3.2^{+4.1}_{-3.1}$		$3.2^{+4.1}_{-3.1}$
$\Delta(1740)P_{31}$[a]	4.9 ± 1.3			
$[\Delta\,\frac{1}{2}^+]_2(1875)$	9.4 ± 0.4	-2.9 ± 0.7		2.9 ± 0.7
$\Delta(1910)P_{31}$****	6.6 ± 1.6			
		p	f	
$[\Delta\,\frac{1}{2}^+]_2(1795)$	8.7 ± 0.2	$0.0^{+0.3}_{-0.0}$	0.0 ± 0.0	$0.0^{+0.3}_{-0.0}$
$\Delta(1600)P_{33}$***	7.6 ± 2.3			
$[\Delta\,\frac{3}{2}^+]_3(1915)$	4.2 ± 0.3	-3.3 ± 0.9	0.7 ± 0.4	3.4 ± 0.9
$\Delta(1920)P_{33}$***	7.7 ± 2.3			
$[\Delta\,\frac{3}{2}^+]_4(1985)$	$3.3^{+0.8}_{-1.1}$	$-4.2^{+2.4}_{-1.7}$	$-0.7^{+0.6}_{-1.2}$	$4.3^{+1.9}_{-2.5}$
		p	f	
$[\Delta\,\frac{5}{2}^+]_1(1910)$	3.4 ± 0.2	-0.5 ± 0.1	0.6 ± 0.3	0.8 ± 0.3
$\Delta(1750)F_{35}$[b]	2.0 ± 0.8			
$\Delta(1905)F_{35}$****	5.5 ± 2.7			
$[\Delta\,\frac{5}{2}^+]_2(1990)$	1.2 ± 0.4	$-7.0^{+5.1}_{-2.9}$	$0.3^{+0.8}_{-0.3}$	$7.0^{+2.9}_{-5.1}$
$\Delta(2000)F_{35}$**	5.3 ± 2.3			
		f	h	
$[\Delta\,\frac{7}{2}^+]_1(1940)]$	7.1 ± 0.1	0.9 ± 0.1	0.0 ± 0.0	0.9 ± 0.1
$\Delta(1950)F_{37}$****	9.8 ± 2.7			

[a] First P_{31} state found in Ref. [1].

[b] Reference [1] finds two F_{35} states: this one and $\Delta(1905)F_{35}$.

should contribute with a strength comparable to that of the neighboring well known second P_{31} state $\Delta(1910)$. The same should be true for the weak second F_{35} state $\Delta(1990)$, which has a large predicted amplitude to decay to $\Delta\eta$, and for the weak second D_{33} state $\Delta(1940)$, which is predicted to show up at least as strongly as the first D_{33} state $\Delta(1700)$ in this channel. In the S_{31} partial wave we predict that the one-star third state $\Delta(2150)$ should show up with greater strength than the well known second state $\Delta(1900)$.

Importantly, Fig. 1 shows that there should be clear signals for two new baryons below 2200 MeV in this channel. The missing fourth P_{33} state $[\Delta\frac{3}{2}^+]_4(1985)$ should contribute with a strength comparable to that of the established third state $\Delta(1920)$. In the D_{33} partial wave the $N=3$ band predicted state $[\Delta\frac{3}{2}^-]_3(2145)$ should also give the dominant contribution.

Figure 2 allows us to reach similar conclusions for the process $N\gamma\rightarrow\Delta\eta$. Here the dominant effect below 2200 MeV is likely to be the weak second F_{35} state $\Delta(1990)$, which is predicted to have a sizeable photocoupling in Ref. [19], and a large $\Delta\eta$ strength. The weak first P_{31} state $\Delta(1740)$ and second D_{33} state $\Delta(1940)$ are, as above, expected to also contribute substantially, with the latter being the dominant effect in its partial wave. The photocouplings for the two new predicted states mentioned above should be small, but it should still be possible to discover a new second D_{35} baryon, as the model state $[\Delta\frac{5}{2}^-]_2(2165)$ is predicted to be the dominant effect in this mass range. Extracting this state from an $N\pi$ experiment is likely to be difficult, as it should have a mass close to the established first D_{35} state $\Delta(1900)$, and we predict small couplings to $N\pi$, so photoproduction shows greater promise for its discovery.

Table II shows that several baryons in the mass region above 2200 MeV should have substantial decay branches to $\Delta\eta$. For example, we see that it may be possible to confirm the one-star state $\Delta(2390)F_{37}$ in a $\Delta\eta$ experiment. We also

TABLE II. Results in the $\Delta\eta$ channel for the lightest few negative-parity Δ resonances of each J in the $N=3$ band, and for the lightest few Δ resonances for J^P values which first appear in the $N=4$, 5 and 6 bands. Notation as in Table I.

Model state $N\pi$ state/rating	$N\pi$	$\Delta\eta$	$\Delta\eta$	$\sqrt{\Gamma^{\rm tot}_{\Delta\eta}}$
		d		
$[\Delta\frac{1}{2}^-]_2(2035)$	1.2 ± 0.2	$1.8^{+0.9}_{-0.7}$		$1.8^{+0.9}_{-0.7}$
$\Delta\frac{1}{2}^-(1900)S_{31}$***	4.1 ± 2.2			
$[\Delta\frac{1}{2}^-]_3(2140)$	$3.1^{+0.4}_{-1.1}$	$-2.4^{+1.0}_{-.6}$		$2.4^{+0.6}_{-1.0}$
$\Delta\frac{1}{2}^-(2150)S_{31}$*	4.0 ± 1.5			
		s	d	
$[\Delta\frac{3}{2}^-]_2(2080)$	2.1 ± 0.1	2.4 ± 0.6	$1.9^{+1.9}_{-1.6}$	$3.1^{+1.8}_{-1.3}$
$\Delta\frac{3}{2}^-(1940)D_{33}$*	3.2 ± 1.4			
$[\Delta\frac{3}{2}^-]_3(2145)$	$2.2^{+0.1}_{-0.3}$	$-1.9^{+0.4}_{-1.2}$	$3.3^{+0.9}_{-1.5}$	3.8 ± 1.4
		d	g	
$[\Delta\frac{5}{2}^-]_1(2155)$	5.2 ± 0.0	1.1 ± 0.3	-0.1 ± 0.0	1.1 ± 0.3
$\Delta\frac{5}{2}^-(1930)D_{35}$***	5.0 ± 2.3			
$[\Delta\frac{5}{2}^-]_2(2165)$	0.6 ± 0.1	$3.7^{+0.9}_{-1.6}$	$1.3^{+1.2}_{-0.9}$	$3.9^{+1.3}_{-1.8}$
$[\Delta\frac{5}{2}^-]_3(2265)$	2.4 ± 0.4	-2.7 ± 0.2	1.2 ± 0.4	2.9 ± 0.4
$[\Delta\frac{5}{2}^-]_4(2325)$	0.1 ± 0.0	$-2.4^{+0.4}_{-0.1}$	$1.1^{+0.7}_{-0.5}$	$2.6^{+0.5}_{-0.6}$
$[\Delta\frac{7}{2}^-]_1(2230)$	2.1 ± 0.6	$3.8^{+0.6}_{-1.5}$	$1.2^{+1.0}_{-0.8}$	$4.0^{+0.9}_{-1.7}$
$[\Delta\frac{7}{2}^-]_2(2295)$	1.8 ± 0.4	$-4.0^{+1.0}_{-0.3}$	$1.5^{+0.9}_{-0.8}$	$4.2^{+0.6}_{-1.1}$
		g	i	
$[\Delta\frac{9}{2}^-]_1(2295)$	4.8 ± 1.3	$2.2^{+2.1}_{-1.2}$	0.0 ± 0.0	$2.2^{+2.1}_{-1.2}$
$\Delta\frac{9}{2}^-(2400)G_{39}$**	4.1 ± 2.1			
		f	h	
$[\Delta\frac{7}{2}^+]_2(2370)$	$1.5^{+0.6}_{-0.9}$	$2.7^{+0.4}_{-0.6}$	0.0 ± 0.0	$2.7^{+0.4}_{-0.6}$
$\Delta\frac{7}{2}^+(2390)F_{37}$*	4.9 ± 2.0			
$[\Delta\frac{7}{2}^+]_3(2460)$	$1.1^{+0.0}_{-0.1}$	-1.6 ± 0.4	$1.0^{+0.9}_{-0.5}$	$1.9^{+0.9}_{-0.6}$
$[\Delta\frac{9}{2}^+]_1(2420)$	1.2 ± 0.4	-0.2 ± 0.1	$0.7^{+0.7}_{-0.4}$	$0.7^{+0.7}_{-0.4}$
$\Delta\frac{9}{2}^+(2300)H_{39}$**	5.1 ± 2.2			
$[\Delta\frac{9}{2}^+]_2(2505)$	0.4 ± 0.1	-3.3 ± 0.7	$0.3^{+0.3}_{-0.1}$	3.3 ± 0.8
		h	j	
$[\Delta\frac{11}{2}^+]_1(2450)$	2.9 ± 0.7	$1.0^{+0.7}_{-0.4}$	0.0 ± 0.0	$1.0^{+0.7}_{-0.4}$
$\Delta\frac{11}{2}^+(2420)H_{3\,11}$****	6.7 ± 2.8			
$[\Delta\frac{13}{2}^+]_1(2880)$	0.8 ± 0.2	0.0 ± 0.0	$1.3^{+0.8}_{-0.6}$	$1.3^{+0.8}_{-0.6}$
$[\Delta\frac{13}{2}^+]_2(2955)$	0.2 ± 0.1	$-2.1^{+0.4}_{-0.2}$	0.3 ± 0.1	$2.1^{+0.2}_{-0.4}$
		i	k	
$[\Delta\frac{13}{2}^-]_1(2750)$	2.2 ± 0.4	$1.6^{+0.7}_{-0.5}$	0.0 ± 0.0	$1.6^{+0.7}_{-0.5}$
$\Delta\frac{13}{2}^-(2750)I_{3\,13}$**	3.7 ± 1.5			
		j	l	
$[\Delta\frac{15}{2}^+]_1(2920)$	1.6 ± 0.3	1.4 ± 0.5	0.0 ± 0.0	1.4 ± 0.5
$\Delta\frac{15}{2}^+(2950)K_{3\,15}$**	3.6 ± 1.5			
$[\Delta\frac{15}{2}^+]_2(3085)$	0.4 ± 0.1	0.4 ± 0.2	0.0 ± 0.0	0.4 ± 0.2

TABLE III. Results for Δ states in the $N=1$ and $N=2$ bands in the $\Delta\omega$ channel. Notation as in Table I.

Model state $N\pi$ state/rating	$\Delta\omega$	$\Delta\omega$	$\Delta\omega$	$\Delta\omega$	$\Delta\omega$	$\Delta\omega$	$\sqrt{\Gamma^{\rm tot}_{\Delta\omega}}$
	$p_{1/2}$	$p_{3/2}$	$f_{5/2}$				
$[\Delta\,\frac{1}{2}^+]_1(1835)$ $\Delta(1740)P_{31}{}^{\rm a}$	$0.0^{+1.1}_{-0.0}$	$0.0^{+0.0}_{-2.2}$	0.0 ± 0.0				$0.0^{+2.2}_{-0.0}$
$[\Delta\,\frac{1}{2}^+]_2(1875)$ $\Delta(1910)P_{31}$****	$0.1^{+0.2}_{-0.1}$	0.0 ± 0.1	0.0 ± 0.0				$0.1^{+0.2}_{-0.1}$
	$p_{1/2}$	$p_{3/2}$	$f_{5/2}$				
$[\Delta\,\frac{3}{2}^+]_3(1915)$ $\Delta(1920)P_{33}$***	0.0 ± 0.0	$-0.1^{+0.1}_{-0.3}$	0.0 ± 0.0	$-0.1^{+0.1}_{-0.2}$	0.0 ± 0.0		$0.1^{+0.3}_{-0.1}$
$[\Delta\,\frac{3}{2}^+]_4(1985)$	$0.8^{+3.8}_{-0.8}$	$0.3^{+1.4}_{-0.3}$	$0.1^{+1.3}_{-0.1}$	$0.0^{+0.0}_{-0.1}$	$-0.1^{+0.1}_{-0.8}$		$0.9^{+4.3}_{-0.9}$
	$f_{1/2}$	$p_{3/2}$	$f_{3/2}$	$p_{5/2}$	$f_{5/2}$	$h_{\frac{5}{2}}$	
$[\Delta\,\frac{5}{2}^+]_1(1910)$ $\Delta(1750)F_{35}{}^{\rm b}$ $\Delta(1905)F_{35}$****	0.0 ± 0.0	$-0.1^{+0.1}_{-0.3}$	0.0 ± 0.0	$-0.1^{+0.1}_{-0.2}$	0.0 ± 0.0	0.0 ± 0.0	$0.1^{+0.3}_{-0.1}$
$[\Delta\,\frac{5}{2}^+]_2(1990)$ $\Delta(2000)F_{35}$**	$0.0^{+0.0}_{-0.5}$	$0.8^{+3.6}_{-0.8}$	$0.1^{+1.5}_{-0.1}$	$-1.3^{+1.3}_{-5.6}$	$-0.1^{+0.1}_{-2.4}$	0.0 ± 0.0	$1.5^{+7.2}_{-1.5}$
	$f_{1/2}$	$f_{3/2}$	$h_{3/2}$	$p_{5/2}$	$f_{5/2}$	$h_{5/2}$	
$[\Delta\,\frac{7}{2}^+]_1(1940)]$ $\Delta(1950)F_{37}$****	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	-1.0 ± 0.2	0.0 ± 0.0	0.0 ± 0.0	1.0 ± 0.3

[a] First P_{31} state found in Ref. [1].

[b] Reference [1] finds two F_{35} states: this one and $\Delta(1905)F_{35}$.

predict that the model states $[\Delta\frac{7}{2}^-]_1(2230)$, $[\Delta\frac{7}{2}^-]_2(2295)$ and $[\Delta\frac{9}{2}^+]_2(2505)$ offer good opportunities for discovery using this final state.

B. $\Delta\omega$ decays

The results for this decay channel are shown in Tables III and IV, and our predictions for the relative contributions of model states below 2200 MeV to pion production of the $\Delta\omega$ final state are illustrated in Fig. 3, and to photoproduction in Fig. 4.

In contrast to the situation for the process $N\pi\rightarrow\Delta\eta$, in Fig. 3 we see that the process $N\pi\rightarrow\Delta\omega$ is likely to get its largest contributions from highly excited negative-parity excited Δ baryons above 2000 MeV. The high effective (nominal) threshold of approximately 1860 (2010) MeV precludes sizeable couplings of states with wave functions predominantly below the $N=3$ band to the $\Delta\omega$ channel (see Table III), although there are some states with amplitudes which grow rapidly away from the threshold, and so will couple if the actual mass is larger than the nominal mass we have used. One exception is the well known first F_{37} state $\Delta(1950)$, which has a small predicted $\Delta\omega$ decay amplitude but a large $N\pi$ amplitude, and so will contribute with appreciable strength to this process.

From Fig. 3 we see that the one-star third S_{31} state $\Delta(2150)$ is predicted to be the dominant effect in the cross section at these energies. Once again, it should also dominate the lower energy behavior of its partial wave, as the well known second state $\Delta(1900)$ should have little or no coupling to $\Delta\omega$. There should also be a clear signal in the D_{33} partial wave for an $N=3$ band state in a $N\pi\rightarrow\Delta\omega$ experiment, as the predicted state $[\Delta\frac{3}{2}^-]_3(2145)$ should give the dominant contribution at lower energies.

Figure 4 illustrates that, with the exception of the well known first F_{37} state $\Delta(1950)$ which also has a substantial photocoupling and so should be obvious in such an experiment, the dominant contributions to $\gamma N\rightarrow\Delta\omega$ are predicted to come from weakly established or entirely new states. Such states also give the dominant contributions in most of the partial waves considered in Fig. 4. It should be possible to confirm the weak second F_{35} state $\Delta(1990)$ and the weak third S_{31} state $\Delta(2150)$. The new model states $[\Delta\frac{3}{2}^-]_3(2145)$ and $[\Delta\frac{5}{2}^-]_2(2165)$ are predicted to give significant contributions to this process and dominate their partial waves at these energies.

Several of the more highly excited states considered here in Table IV have appreciable couplings to the $\Delta\omega$ channel. It may be possible to confirm the weak states $\Delta(2400)G_{39}$ (two stars), and $\Delta(2390)F_{37}$ (one star) using this final state, or perhaps even the very highly excited states $\Delta(2750)I_{313}$ and $\Delta(2950)K_{315}$ (both two-star states). Our results predict that a $\Delta\omega$ experiment may also be able to discover several higher mass predicted states, the most interesting of which are $[\Delta\frac{5}{2}^-]_3(2265)$, the two states $[\Delta\frac{7}{2}^-]_1(2230)$ and $[\Delta\frac{7}{2}^-]_2(2295)$, and $[\Delta\frac{9}{2}^+]_2(2505)$.

TABLE IV. Results in the $\Delta\omega$ channel for the lightest few negative-parity Δ resonances of each J in the $N=3$ band, and for the lightest few Δ resonances for J^P values which first appear in the $N=4$, 5 and 6 bands. Notation as in Table I.

Model state $N\pi$ state/rating	$\Delta\omega$	$\Delta\omega$	$\Delta\omega$	$\Delta\omega$	$\Delta\omega$	$\Delta\omega$	$\sqrt{\Gamma^{\rm tot}_{\Delta\omega}}$
	$s_{1/2}$	$d_{3/2}$	$d_{5/2}$				
$[\Delta\frac{1}{2}^-]_2(2035)$	$-0.2^{+0.2}_{-0.6}$	$0.0^{+0.0}_{-0.2}$	0.0 ± 0.0				$0.2^{+0.7}_{-0.2}$
$\Delta\frac{1}{2}^-(1900)S_{31}^{***}$							
$[\Delta\frac{1}{2}^-]_3(2140)$	-2.1 ± 0.7	0.1 ± 0.0	$5.7^{+5.8}_{-4.9}$				$6.1^{+5.8}_{-4.4}$
$\Delta\frac{1}{2}^-(2150)S_{31}^{*}$							
	$d_{1/2}$	$d_{3/2}$	$d_{5/2}$	$g_{5/2}$			
$[\Delta\frac{3}{2}^-]_2(2080)$	$0.1^{+1.4}_{-0.1}$	$-0.1^{+0.1}_{-2.1}$	0.0 ± 0.0	0.0 ± 0.0			$0.1^{+2.5}_{-0.1}$
$\Delta\frac{3}{2}^-(1940)D_{33}^{*}$							
$[\Delta\frac{3}{2}^-]_3(2145)$	6 ± 0.6	0.2 ± 0.3	$-4.2^{+3.7}_{-4.5}$	0.0 ± 0.0			$4.2^{+4.5}_{-3.7}$
	$d_{1/2}$	$d_{3/2}$	$g_{3/2}$	$s_{5/2}$	$d_{5/2}$	$g_{5/2}$	
$[\Delta\frac{5}{2}^-]_1(2155)$	0.0 ± 0.1	0.0 ± 0.1	0.0 ± 0.0	$-1.0^{+0.7}_{-1.4}$	-0.1 ± 0.0	0.0 ± 0.0	$1.0^{+1.4}_{-0.7}$
$\Delta\frac{5}{2}^-(1930)D_{35}^{***}$							
$[\Delta\frac{5}{2}^-]_2(2165)$	$-1.0^{+0.9}_{-1.0}$	$-1.0^{+0.9}_{-1.0}$	$-0.5^{+0.5}_{-1.5}$	-3.3 ± 0.8	$-1.8^{+1.5}_{-1.6}$	0.0 ± 0.0	$4.0^{+2.3}_{-1.5}$
$[\Delta\frac{5}{2}^-]_3(2265)$	1.7 ± 0.5	-0.7 ± 0.2	0.3 ± 0.2	$-0.5^{+0.1}_{-0.3}$	$-3.0^{+0.9}_{-0.7}$	$-2.4^{+1.3}_{-1.9}$	$4.3^{+1.9}_{-1.5}$
$[\Delta\frac{5}{2}^-]_4(2325)$	-0.2 ± 0.1	-1.5 ± 0.7	$-0.2^{+0.2}_{-0.3}$	$1.0^{+0.7}_{-0.2}$	0.2 ± 0.1	$-1.1^{+0.8}_{-1.6}$	$2.1^{+1.8}_{-1.0}$
	$g_{1/2}$	$d_{3/2}$	$g_{3/2}$	$d_{5/2}$	$g_{5/2}$	$i_{5/2}$	
$[\Delta\frac{7}{2}^-]_1(2230)$	$0.1^{+0.2}_{-0.1}$	-0.5 ± 0.3	$0.3^{+0.6}_{-0.3}$	-4.1 ± 2.2	$-1.4^{+1.1}_{-2.4}$	0.0 ± 0.0	$4.4^{+3.0}_{-2.4}$
$[\Delta\frac{7}{2}^-]_2(2295)$	$0.1^{+0.2}_{-0.1}$	-0.5 ± 0.3	$0.3^{+0.6}_{-0.3}$	-4.1 ± 2.2	$-1.4^{+1.1}_{-2.4}$	0.0 ± 0.0	$4.4^{+3.0}_{-2.4}$
	$g_{1/2}$	$g_{3/2}$	$i_{3/2}$	$d_{5/2}$	$g_{5/2}$	$i_{5/2}$	
$[\Delta\frac{9}{2}^-]_1(2295)$	$0.9^{+1.1}_{-0.7}$	$0.5^{+0.6}_{-0.4}$	0.0 ± 0.0	$-9.5^{+4.9}_{-1.4}$	$-1.9^{+1.5}_{-2.2}$	0.0 ± 0.0	$9.8^{+2.2}_{-5.1}$
$\Delta\frac{9}{2}^-(2400)G_{39}^{**}$							
	$f_{1/2}$	$f_{3/2}$	$h_{3/2}$	$p_{5/2}$	$f_{5/2}$	$h_{5/2}$	
$[\Delta\frac{7}{2}^+]_2(2370)$	1.4 ± 0.7	0.8 ± 0.4	0.0 ± 0.0	$-3.0^{+0.2}_{-1.4}$	$-3.1^{+1.7}_{-1.5}$	0.0 ± 0.0	$4.6^{+2.1}_{-1.4}$
$\Delta\frac{7}{2}^+(2390)F_{37}^{*}$							
$[\Delta\frac{7}{2}^+]_3(2460)$	0.1 ± 0.0	-1.0 ± 0.6	$-0.2^{+0.2}_{-0.3}$	0.3 ± 0.0	$-1.6^{+0.9}_{-0.8}$	$-1.1^{+0.9}_{-1.4}$	$2.3^{+1.6}_{-1.3}$
	$h_{1/2}$	$f_{3/2}$	$h_{3/2}$	$f_{5/2}$	$h_{5/2}$	$j_{5/2}$	
$[\Delta\frac{9}{2}^+]_1(2420)$	$0.2^{+0.4}_{-0.1}$	$-1.3^{+0.8}_{-1.2}$	$-0.1^{+0.1}_{-0.2}$	$-1.4^{+0.9}_{-1.3}$	$-0.3^{+0.3}_{-0.7}$	0.0 ± 0.0	$1.9^{+2.0}_{-1.3}$
$\Delta\frac{9}{2}^+(2300)H_{39}^{**}$							
$[\Delta\frac{9}{2}^+]_2(2505)$	-0.4 ± 0.3	$2.4^{+0.5}_{-0.9}$	$1.0^{+0.9}_{-0.6}$	$-3.1^{+1.2}_{-0.7}$	$-1.3^{+0.8}_{-1.1}$	0.0 ± 0.0	$4.3^{+1.5}_{-1.8}$
	$h_{1/2}$	$h_{3/2}$	$j_{3/2}$	$f_{5/2}$	$h_{5/2}$	$j_{5/2}$	
$[\Delta\frac{11}{2}^+]_1(2450)$	0.4 ± 0.3	0.2 ± 0.2	0.0 ± 0.0	$-5.1^{+2.2}_{-1.6}$	$0.8^{+0.6}_{-0.5}$	0.0 ± 0.0	$5.2^{+1.7}_{-2.3}$
$\Delta\frac{11}{2}^+(2420)H_{3\,11}^{****}$							
	$j_{1/2}$	$h_{3/2}$	$j_{3/2}$	$h_{5/2}$	$j_{5/2}$	$l_{5/2}$	
$[\Delta\frac{13}{2}^+]_1(2880)$	$0.6^{+0.6}_{-0.3}$	-1.3 ± 0.5	$-0.3^{+0.2}_{-0.3}$	-1.5 ± 0.5	$-0.9^{+0.5}_{-0.9}$	0.0 ± 0.0	$2.3^{+1.3}_{-0.9}$
$[\Delta\frac{13}{2}^+]_2(2955)$	$-0.5^{+0.3}_{-0.4}$	1.6 ± 0.4	$1.2^{+1.0}_{-0.6}$	-1.9 ± 0.6	$-1.4^{+0.7}_{-1.1}$	0.0 ± 0.0	$3.2^{+1.5}_{-1.2}$
	$i_{1/2}$	$i_{3/2}$	$k_{3/2}$	$g_{5/2}$	$i_{5/2}$	$k_{5/2}$	
$[\Delta\frac{13}{2}^-]_1(2750)$	$0.6^{+0.4}_{-0.2}$	0.3 ± 0.2	0.0 ± 0.0	$-4.3^{+0.8}_{-1.0}$	$-1.1^{+0.4}_{-0.6}$	0.0 ± 0.0	$4.5^{+1.2}_{-0.9}$
$\Delta\frac{13}{2}^-(2750)I_{3\,13}^{**}$							
	$j_{1/2}$	$j_{3/2}$	$l_{3/2}$	$h_{5/2}$	$j_{5/2}$	$l_{5/2}$	
$[\Delta\frac{15}{2}^+]_1(2920)$	0.7 ± 0.3	0.3 ± 0.2	0.0 ± 0.0	-3.6 ± 0.8	$1.2^{+0.6}_{-0.4}$	0.0 ± 0.0	3.9 ± 1.0
$\Delta\frac{15}{2}^+(2950)K_{3\,15}^{**}$							
$[\Delta\frac{15}{2}^+]_2(3085)$	0.2 ± 0.1	0.1 ± 0.1	0.0 ± 0.0	$-1.2^{+0.3}_{-0.2}$	-0.4 ± 0.2	0.0 ± 0.0	1.3 ± 0.3

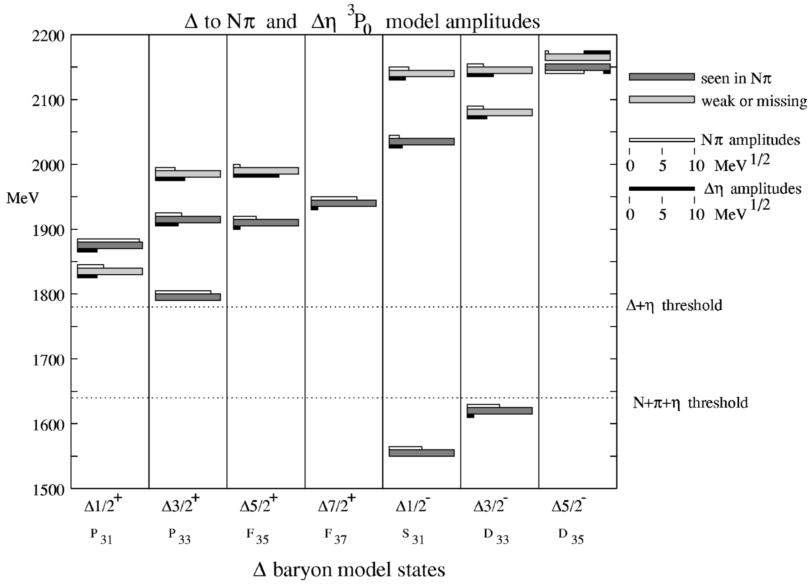

FIG. 1. Mass predictions, and $N\pi$ and $\Delta\eta$ decay amplitude predictions for Δ baryons up to 2200 MeV, sorted according to spin and parity. Heavy uniform-width bars show the predicted masses of states with well established counterparts from partial-wave analyses, light bars those of states which are weakly established or missing. The length of the thin white bar gives our prediction for each state's $N\pi$ decay amplitude, and that of the thin black bar gives our prediction for its $\Delta\eta$ decay amplitude. States with significant amplitudes for both decays should contribute strongly to the process $\pi N \rightarrow \Delta\eta$.

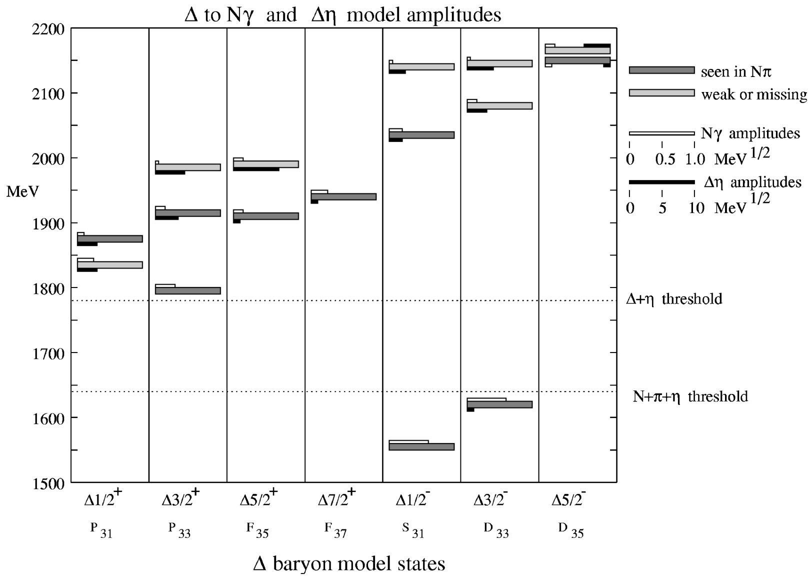

FIG. 2. Mass predictions, and $N\gamma$ and $\Delta\eta$ decay amplitude predictions for Δ baryons up to 2200 MeV. Notation as in Fig. 1 except that the length of the thin white bar gives our prediction for each state's $N\gamma$ decay amplitude. States with significant amplitudes for both decays should contribute strongly to the process $\gamma N \rightarrow \Delta\eta$.

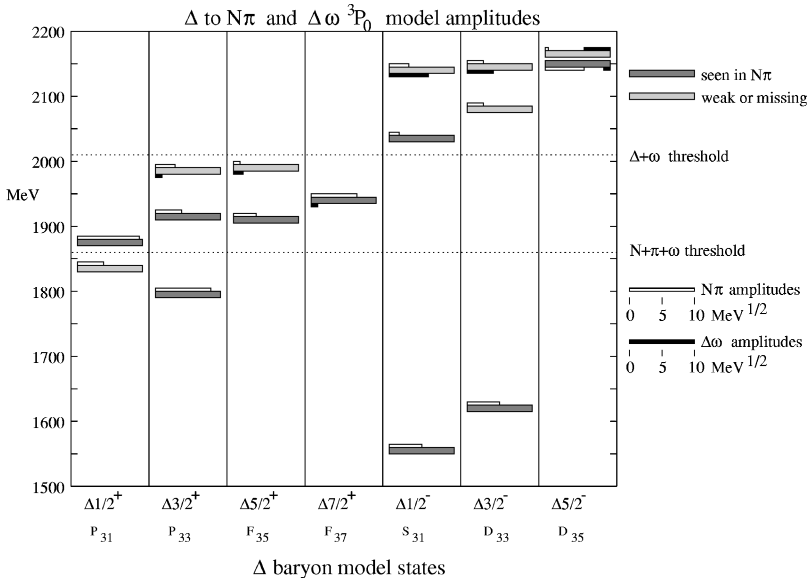

FIG. 3. Mass predictions, and $N\pi$ and $\Delta\omega$ decay amplitude predictions for Δ baryons up to 2200 MeV. Notation as in Fig. 1 except that the length of the thin black bar gives our prediction for each state's $\Delta\omega$ decay amplitude. States with significant amplitudes for both decays should contribute strongly to the process $\pi N \rightarrow \Delta\omega$.

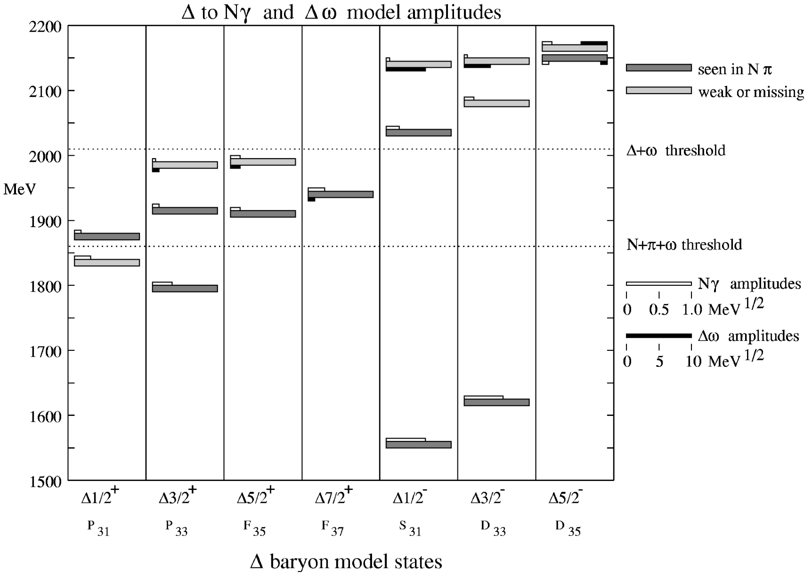

FIG. 4. Mass predictions, and $N\gamma$ and $\Delta\omega$ decay amplitude predictions for Δ baryons up to 2200 MeV. Notation as in Fig. 2 except that the length of the thin black bar gives our prediction for each state's $N\omega$ decay amplitude. States with significant amplitudes for both decays should contribute strongly to the process $\gamma N \rightarrow \Delta\omega$.

C. Conclusions

Our results show that there should be good signals for the presence of the weakly established first P_{31} baryon $\Delta(1740)$, the weak second F_{35} state $\Delta(1990)$, the weak third S_{31} state $\Delta(2150)$, and the weak second D_{33} state $\Delta(1940)$ in pion and photoproduction of the final state $\Delta\eta$. With the exception of $\Delta(2150)$, these states should appear in both experiments. There should also be clear signals in pion production of $\Delta\eta$ for two new baryons predicted by our model, which are the missing fourth P_{33} state $[\Delta\frac{3}{2}^+]_4(1985)$ and a third D_{33} state $[\Delta\frac{3}{2}^-]_3(2145)$. Photoproduction of this final state should yield strong evidence for a second D_{35} baryon $[\Delta\frac{5}{2}^-]_2(2165)$. Given that in several cases weakly established or new states are predicted to be the dominant effects in their partial waves, a partial wave analysis would facilitate their confirmation or discovery. This requires high-quality data for polarization observables.

Interestingly, the same states should also be accessible in pion and photoproduction of the final state $\Delta\omega$, with the exception of the first P_{31} $\Delta(1740)$ and the fourth P_{33} state $[\Delta\frac{3}{2}^+]_4(1985)$, which do not couple appreciably to this final state. Although more difficult, a $\Delta\omega$ experiment has the advantage of a higher threshold, so that weakly established or new states are almost always the dominant effects in their partial waves. This will make their extraction from a partial-wave analysis significantly less complicated than in final states with lower thresholds.

Amplitudes for all states to couple to the $\Delta\eta'$ channel are small, largely due to the high threshold. Nevertheless, it is worth mentioning that the combination of a high threshold and isospin selectivity could make this channel useful for seeking heavier new Δ resonances. Because all amplitudes in this channel are small, one would expect that the cross section will also be small. However, in various partial waves, one may find that one or more new resonances may dominate the cross section.

Reconstruction of the $\Delta\eta$ and $\Delta\omega$ final states will be difficult due to the final state particle multiplicity, and the presence of neutral particles in the case of electromagnetic production from the proton. However it may be that the extraction of information about these important new baryon states from an analysis of the results of such an experiment is considerably less complicated than using channels with fewer final state particles. It is also interesting that states with small but non-negligible $N\pi$ couplings which are missing in pion-nucleon elastic scattering may be observable with these final states. This indicates that it is worthwhile to consider developing such experiments.

ACKNOWLEDGMENTS

The importance of these channels was pointed out to us by Professor D. Mark Manley and Professor B. Nefkens. This work was supported in part by the Florida State University Supercomputer Computations Research Institute which is partially funded by the Department of Energy through Contract DE-FC05-85ER250000 (S.C.); the U.S. Department of Energy under Contract No. DE-FG05-86ER40273 (S.C.); the National Science Foundation through Grant No. PHY-9457892 (W.R.); the U.S. Department of Energy under Contract No. DE-AC05-84ER40150 (W.R.); and by the U.S. Department of Energy under Contract No. DE-FG02-97ER41028 (W.R.).

---

[1] D. M. Manley and E. M. Saleski, Phys. Rev. D **45**, 4002 (1992).

[2] N. Isgur and G. Karl, Phys. Lett. **72B**, 109 (1977); **74B**, 353 (1978); Phys. Rev. D **18**, 4187 (1978); **19**, 2653 (1979); D. P. Stanley and D. Robson, Phys. Rev. Lett. **45**, 235 (1980); C. P. Forsyth and R. E. Cutkosky, *ibid.* **46**, 576 (1981); Z. Phys. C **18**, 219 (1983); J. Carlson, J. Kogut, and V. R. Pandharipande, Phys. Rev. D **27**, 233 (1983); **28**, 2807 (1983); R. Sartor and

Fl. Stancu, *ibid.* **31**, 128 (1985); **33**, 727 (1986).

[3] S. Capstick and N. Isgur, Phys. Rev. D **34**, 2809 (1986).

[4] See, for example, A. Le Yaouanc, L. Oliver, O. Pène and J. C. Raynal, *Hadron Transitions In The Quark Model* (Gordon and Breach, New York, 1988). This work contains many references to hadron decay models. Other references to hadron transition models are: A. Le Yaouanc, L. Oliver, O. Pène, and J. C. Raynal, Phys. Rev. D **8**, 2223 (1973); **9**, 1415 (1974); **11**, 680 (1975); **11**, 1272 (1975); E. Eichten, K. Gottfried, T. Kinoshita, K. Lane, and T. M. Yan, *ibid.* **17**, 3090 (1978).

[5] R. Koniuk and N. Isgur, Phys. Rev. D **21**, 1868 (1980).

[6] Fl. Stancu and P. Stassart, Phys. Rev. D **38**, 233 (1988); **39**, 343 (1989); **41**, 916 (1990); **42**, 1521 (1990).

[7] S. Capstick and W. Roberts, Phys. Rev. D **47**, 1994 (1993).

[8] R. Bijker, F. Iachello, and A. Leviatan, Phys. Rev. D **55**, 2862 (1997).

[9] N. Isgur, in *Proceedings of the CEBAF/SURA 1984 Summer Workshop*, Newport News, Virginia, 1984, edited by F. Gross and R. R. Whitney (CEBAF, Newport News, 1984).

[10] J. Napolitano *et al.*, CEBAF proposal 93-033.

[11] S. Capstick and W. Roberts, Phys. Rev. D **49**, 4570 (1994).

[12] S. Dytman *et al.*, CEBAF proposal 89-039.

[13] B. G. Ritchie *et al.*, CEBAF proposal 91-008.

[14] V. Burkert *et al.*, CEBAF proposal 91-024.

[15] J. Napolitano (private communication).

[16] B. Nefkens (private communication).

[17] Particle Data Group, R. M. Barnett *et al.*, Phys. Rev. D **54**, 1 (1996).

[18] R. Kokoski and N. Isgur, Phys. Rev. D **35**, 907 (1987).

[19] S. Capstick, Phys. Rev. D **46**, 1965 (1992); **46**, 2864 (1992).