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# HADRON SPECTROSCOPY*

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## ABSTRACT

Recent experimental and theoretical developments in the field of hadronic resonances are reviewed.

## INTRODUCTION

This review will deal with new developments in the mesons (Section II), the baryons (Section III), and in resonance theory (Section IV). In past years, these subjects were generally covered by three different rapporteurs. Consequently, I must apologize for being brief on some subjects, referring the readers to some excellent "mini-reports" that cover certain topics in more detail.

The field of hadron spectroscopy no longer consists of "bump-hunting". The pattern of resonances is largely filled in and hasn't changed much recently. The emphasis has shifted instead to more detailed questions regarding the structure of pionic decays and electromagnetic transitions. These problems are of considerable interest, just as atomic spectral line intensities and selection rules played a role in the development of quantum mechanics.

Experimental and theoretical developments in this new area of resonance physics have kept pace with one another. The study of the decays of the B meson, and of the reactions $\pi N \rightarrow \pi\Delta$ and $\gamma N \rightarrow \pi N$ in the resonance region, have been matched by renewed interest in symmetries beyond SU(3) which can explain the new data.

Older questions of resonance physics continue to receive attention. The successful classification of states according to the quark model is by now a compelling regularity of the lowest-lying mesons (below ~1.7 GeV) and baryons (below ~2 GeV). The gaps in this scheme are continuing to be filled, while studies of "exotic" states — ones that do not fit the scheme — are proceeding, and within the next year perhaps one will finally have evidence for one or two exotic baryon isomultiplets. In contrast, nearly thirty meson isomultiplets and fifty baryon isomultiplets have been conclusively observed which can be regarded as levels of a quark and an antiquark ($q\bar{q}$) or three quarks (qqq), respectively.[1,2]

## MESONS

Some new developments in meson resonances are shown in Table I.

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Table I New meson data

| $L(q\bar{q})$ | $J^{PC}$ values | Remarks |
|---|---|---|
| 1 | $1^{+-}$ | New $B \rightarrow \omega\pi$ analyses; predictions |
| | $1^{++}$ | Predictions for $A_1$ decay |
| | $0^{++}$ | $\pi\pi$, $K\pi$ scattering<br>$\delta \rightarrow \eta\pi$ observed again |
| 2 | $3^{--}$ | Firmer evidence for g, $K_N$ |
| | $2^{-+}$ | Question of resonant nature of $A_3$ |
| | $1^{--}$ | $\rho'$? [Could also be kinematic effect or $q\bar{q}$ (L=0) state.] |
| Other effects, $J^{PC}$ uncertain | | Narrow bump in $\sigma_T(\bar{p}p)$, $m \sim 1930$ GeV |
| | | New $\bar{p}p \rightarrow \pi^+\pi^-$, $K^+K^-$ differential cross sections, 0.8 to 2.4 GeV/c |
| | | Possible $J \geq 4$ $K_N(2100)$ |

1. Analyses of B decays

The B(1235) is a resonance whose $J^P$ is almost certainly $1^+$, and which decays to $\omega\pi$.[3,4] The helicity structure of the $\omega$'s is of interest in many models and higher symmetries.

We may define normalized helicity amplitudes $F_\lambda$ such that

$$|F_0|^2 + 2|F_1|^2 = 1 . \quad (1)$$

A purely S-wave decay corresponds to $|F_0|^2 = |F_1|^2 = 1/3$. $SU(6)_W$, by virtue of its selection rule demanding that the third component of quark spin be conserved [$\Delta S_z = 0$], implies $|F_0|^2 = 1$. In various new theories, $|F_0|^2$ need not be 1 but is constrained by other data. If we call the orbital angular momentum of quarks in a hadron L, $|F_0|^2$ turns out to be sensitive to $\Delta L_z = 0$ and $|F_1|^2$ to $\Delta L_z = \pm 1$ transitions. The latter are forbidden in $SU(6)_W$, but are certainly important, as we can gauge from $B \rightarrow \omega\pi$ data.

As of last year,[3] most analyses agreed that $|F_0|^2$ was less than 1/3, implying a detectable amount of D wave in B decay. One analysis (of 7 GeV/c $\pi^+p$ data) seemed to imply no D wave at all.

Recently the 7 GeV/c $\pi^+p$ data have been re-analyzed, leading to two values of $|F_0|^2$ in substantial accord with one another: depending on the method of analysis,[4,5]

$$|F_0|^2 = 0.16 \pm 0.04 \quad (2)$$

or

$$|F_0|^2 = 0.12 \pm 0.04 \tag{3}$$

The former result allows for coherently produced $1^-$ and $0^-$ $\omega\pi$ background, while the latter allows for all $J^P$ in the background but without interference. We have used the result (2) below for the sake of definiteness.

A new contribution from the Weizmann Institute[6] has studied $\pi^+p \to B^+p$ at 5 GeV/c and finds

$$|F_0|^2 = 0.01 \pm 0.07 \tag{4}$$

The two values, Eqs. (2) and (4), are shown in Fig. 1.

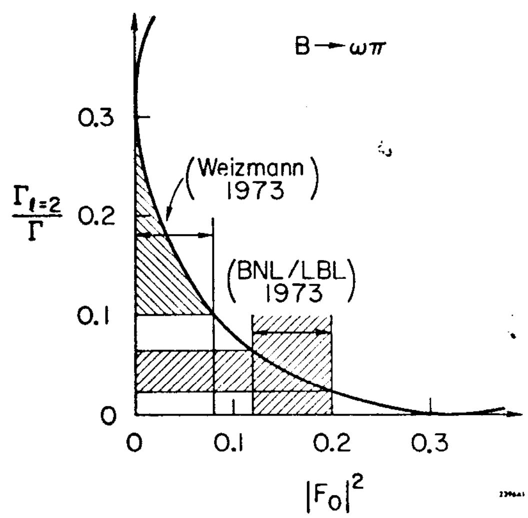


FIG. 1-- Values of $|F_0|^2$ obtained in analyses of $B \to \omega\pi$. LBL: Ref. 5; Weizmann: Ref. 6. The curve shows the fraction of D-wave ($\ell$=2) in the decay for each value of $|F_0|^2$.

Previous world data are compared with the new results in Table II (compiled from Ref. 3). The B decay involves roughly 6% D-wave $\omega\pi$, with $|F_0|^2 = 0.13 \pm 0.05$. (The errors are scaled because of the discrepancy between Ref. (5) and (6). The width is slightly above that of Ref. (7).

A recent study of $\pi^-n \to B^-p\pi^-$ is consistent with $|F_0|^2 = 0$, but no detailed analysis has been performed.[8]

Figure 1 and Table II show that the transversely polarized $\omega$'s certainly dominate in $B \to \omega\pi$. The world average for $|F_0|^2$ is now four standard deviations away from pure S wave; moreover, the Weizmann Institute group has yet to analyze all of their data. There has also been a high-statistics study of $\pi^+p$ interactions at 13 GeV/c presented to this conference,[9] whose B signal is appreciable. We may expect some additions to Table II in the next year or two.

## 2. Predictions for $A_1$ and B decays

The ingredients for these predictions (whose theoretical basis will be discussed in Section IV) are: (i) $SU(6)_W \times 0(3)$ for the initial and final states, and (ii) single-quark selection rules for pion emission. The second is weaker than the assumption of an $SU(6)_W$-invariant decay. In addition we must fix parameters of the theory via one D-wave decay (e.g., $f_0 \to \pi\pi$ or $A_2 \to \rho\pi$) and one S-wave decay. The best source of the latter is the

Table II World B decay data

| Reference[3] | Events | $\Gamma_B$ | $\lvert F_0 \rvert^2$ | $\Gamma^{(\omega\pi)}_{\ell=2}/\Gamma^{(\omega\pi)}$ |
|---|---|---|---|---|
| Illinois, 1970 | 686 ±35 | 144 ±21 | .184 ±.051 | 3% |
| BDNPT 1970 | 226 ±20 | 120 ±20 | .06 ±.10 | 13% |
| DGHMS 1972 | 130 ±14 | 125 ±30 | .09 ±.07 | 9% |
| BNL/LBL 1973[5] | ~1200 | 150 ±20 | .16 (or .12) ±.04 | 4% |
| Weizmann, 1973[6] | ≥ 500 | 156 ±22 | .01 ±.07 | 25% |
| Total or average | ~2750 | 141[a] ±14 | .13 ±.05 | 6% |

[a]Reference (7) quotes an average of 118 ± 8 MeV.

estimate

$$\Gamma_{\ell=0}\,(B \rightarrow \omega\pi) \simeq 130 \text{ MeV}, \tag{5}$$

based on Table II.

The output involves all partial widths for the decays

$$\begin{aligned} &2^{++} \rightarrow 1^-0^-,\ 0^-0^- \\ &1^{+\pm} \rightarrow 1^-0^- \\ &0^{++} \rightarrow 0^-0^- \end{aligned} \tag{6}$$

as well as the helicity structure for $1^{+\pm} \rightarrow 1^-0^-$.

There are different theories giving such predictions. They have the same algebraic structure but different kinematic factors. In the covariant approach of Ref. (10), based on a quark-pair-creation model suggested earlier,[11] the partial widths $\Gamma_\ell$ for decays into final states with orbital angular momentum $\ell$ behave as

$$\Gamma_\ell \sim p^{2\ell+1}/m_A^2 \quad \text{(Ref. 10)}\,, \tag{7}$$

where p is the magnitude of the CM 3-momentum and A is the decaying resonance. In the more recent approach[12-14] based on the work of Melosh[15] and PCAC, these partial widths all behave as[16]

$$\Gamma_\ell \sim p(m_A^2 - m_B^2)^2/m_A^2 \tag{8}$$

for <u>any</u> decay $A \to B\pi$, no matter what the $\ell$ of the $B\pi$ system.

Both theories have in common the addition of a new term describing pion emission:

$$\Delta L_z = \pm 1 \tag{9}$$

which allows for the transverse motion of quarks in an L-excited hadron. The old, $SU(6)_W$-invariant term with

$$\Delta L_z = 0 \tag{10}$$

is also retained.

The resulting predictions are shown in Table III.

Table III Predictions for $A_1$ and B decays[2]

| | | $A_1(1100) \to \rho\pi$ | $B(1235) \to \omega\pi$ |
|---|---|---|---|
| $\Gamma_\ell = 0$ | $p^{2\ell+1}$ | $460 \pm 70$ | $130 \pm (\sim 20)$ input |
| | PCAC | $175 \pm 25$ | |
| | Expt. | ? | |
| $\Gamma_{\ell=2}$ | $p^{2\ell+1}$ | $\approx 2$ | 14 (from $A_2 \to \rho\pi$, or $f_0 \to \pi\pi$) |
| | PCAC | $\approx 8$ | 24 (from $A_2 \to \rho\pi$, or $f_0 \to \pi\pi$) |
| | Expt. | ? | $\approx 8$ |
| $\lvert F_0 \rvert^2$ | $p^{2\ell+1}$ | .40 | .08 |
| | PCAC | .54 | .04 |
| | Expt. | ? | $.13 \pm .05$ |

Phase constraint (Ref. 10):

$$2\left(\frac{F_1}{F_0}\right)_{A_1 \to \rho\pi} = \left(\frac{F_0}{F_1}\right)_{B \to \omega\pi} + 1 \ .$$

(Exact in PCAC approach;[12-14] approximate in $p^{2\ell+1}$ approach.[10])

Table III indicates a rather prominent and well-defined $A_1$, especially in the PCAC approach (which has some other advantages). The D-wave admixture in $A_1 \rightarrow \rho\pi$ should be clearly visible. The input (5) may have been an overestimate, as it would seem difficult to hide so broad an $A_1$ under diffractive background. (Such background is almost certainly present in $\pi^- p \rightarrow \rho^0 \pi^- p$.[17]) The "resonant" $A_1$ still has not shown up, and if it goes undetected a while longer we should begin to worry.

One further test of these predictions involves decays of $0^+$ mesons, to which we now turn.

## 3. Predictions for $\delta(970) \rightarrow \eta\pi$ and $K_N(0^+) \rightarrow K\pi$

Table IV shows the status of some predictions similar to those of Table III but for $0^+$ decays.

Table IV

| | $\Gamma(\delta(970) \rightarrow \eta\pi)$ (MeV) | $\Gamma(K_N(1100) \rightarrow K\pi)$ (MeV) |
|---|---|---|
| $p^{2\ell+1}$ | $185 \pm 30$ | $450 \pm 70$ |
| PCAC | $90 \pm 15$ | $485 \pm 75$ |
| Expt. | $60^{+50}_{-30}$ [a] | ? |

[a] Ref. 18.

The experimental width for $\delta$ (assuming 100% $\eta\pi$ decay), is based on a new experiment[18] which studies

$$\begin{array}{l} \pi^- p \rightarrow \delta^- p \\ \qquad\quad \lfloor\!\rightarrow \eta\,\pi^- \\ \qquad\qquad\quad \lfloor\!\rightarrow \gamma\gamma \end{array} \tag{11}$$

at 4.5 GeV/c, resulting in a cross section of only about 2$\mu$b for $\delta^-$ production. Reference 7 quotes $\Gamma_\delta = 50 \pm 30$ MeV.

It thus appears that unless the B is <u>much</u> narrower than in Eq. (5), the $p^{2\ell+1}$ factor is unreliable for S-wave decays, and should be replaced by the PCAC factor of Eq. (8).

The prediction of a relatively wide $K_N \rightarrow K\pi$ is common to both approaches, and should be testable in the near future when precise studies of $K\pi$ scattering become available. At present, all we know of the $0^+$ $K\pi$ system is that it has no resonances hiding under the $K^*(890)$,[19] and the $K\pi$ phase shift stays areound $70^\circ$ from 1100 to 1300 MeV.[7] This behavior is reminiscent of that of the $0^+$ I=0 $\pi\pi$ phase shift around and above the $\epsilon$ (700).

## 4. $\pi\pi$ scattering

Recent high-statistics samples of data have been analyzed in[20]

$$\pi^+ p \rightarrow \pi^+ \pi^- \Delta^{++} \tag{12}$$

and[2]

$$\pi^- p \rightarrow \pi^+ \pi^- n \tag{13}$$

These give rise to three I=Y=0 candidates for $0^{++}$ mesons, as shown in Table V.

Table V $0^{++}$ I=Y=0 candidates

| Name (mass) | Width (MeV) | Decay mode(s) |
|---|---|---|
| $\epsilon$(700) | $\gtrsim 350$ | $\pi\pi$ |
| S*(997) | 10 to 50 | $K\bar{K}$ ($\pi\pi$ weak) |
| $\epsilon$'(1240) | ~ 200 | $\pi\pi$ ($K\bar{K}$ weak) |

The Argand circle for the I=Y=0 S-wave amplitude is shown near the mass of the $\epsilon$'(1240) in Fig. 2 (from Ref. 21).

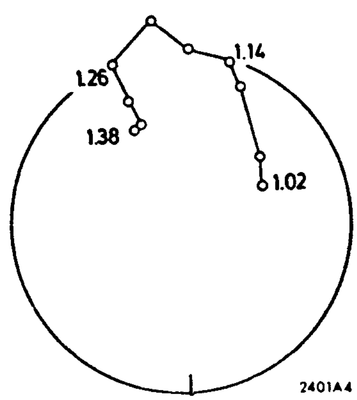


FIG. 2--Argand circle for I=Y=0 S-wave $\pi\pi$ amplitude near the mass of $\epsilon$'(1240).[21]

The existence of the S-wave state under the $f_0$ has been noted[22] and discussed theoretically[23] before. Three I=Y=0 $0^{++}$ states are an embarrassment to the quark model, which predicts only two. The additional state can be a "dilaton", i.e., a Goldstone boson of spontaneously broken scale invariance.[24]

A hypothetical $0^{++}$ "decimet" (nonet plus singlet) is shown in Fig. 3. It is interesting that the masses of the nine states at the top of the figure are consistent with those of an "ideal" nonet. On the other hand, as Table V shows, their couplings are quite substantially different from what we would expect from such a nonet. This can be ascribed to mixing with the additional "dilaton". Quantitatively, the coupling of the dilaton to pairs of pseudoscalar mesons must be quite strong in order for this scheme to work, leading to an $\epsilon(700)$ which is more broad than it is massive! (See Ref. 2.)

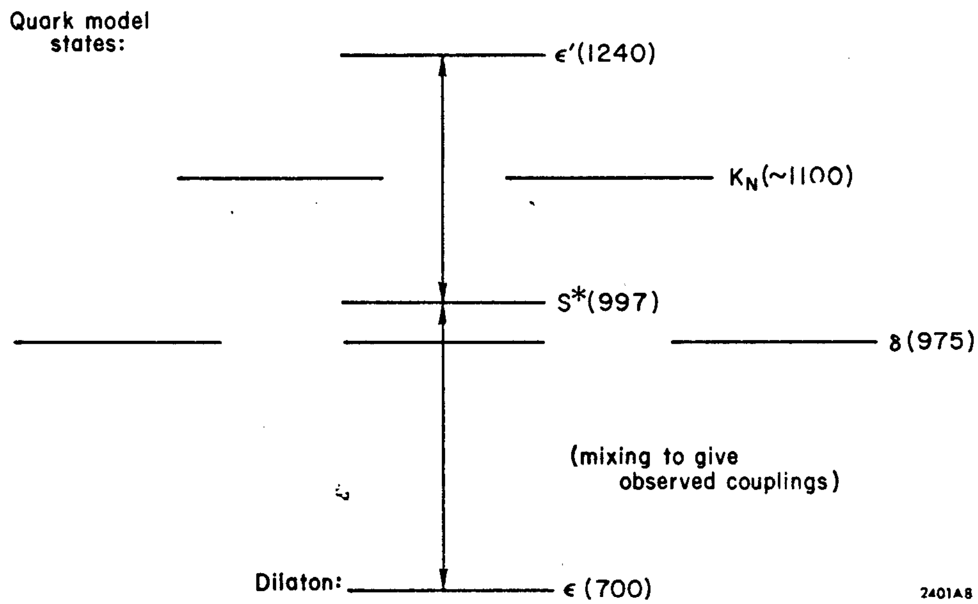


FIG. 3--Hypothetical $0^{++}$ nonet plus singlet.

5. <u>Even-G I=1 mesons, 1.6-1.8 GeV</u>

The Purdue group has presented a study of mesonic states in the "R" mass region, based on a 750,000-picture 13 GeV/c $\pi^+p$ bubble chamber exposure.[9] The final states they discuss are shown in Table IV.

The masses and widths of the three latter final states are compatible with one another ($m \simeq 1680$ MeV, $\Gamma \simeq 100$ MeV), but the $\pi\pi$ effect seems somewhat lighter ($m \simeq 1630$ MeV) and narrower ($\Gamma \simeq 40$ MeV) than the others. In Table IV we have indicated the possible orbital angular momenta between the two final particles for various states expected in the quark model. Quite a few questions are left unanswered by the Purdue data.

(a). <u>$\pi\pi$ final state</u>. Partial-wave analyses favor a $3^-$ state, confirmed here. The CERN-Munich experiment, reaction (13), also may see some evidence for a $1^-$ state near this mass.[25,26] What are the bounds on the existence of such a state here?

(b). <u>$\omega\pi$ final state</u>. The angular distributions are compatible with being due entirely to $3^-$, but bounds on $1^-$ and $2^-$ states are needed.

Table VI Study of the R region, $I^G=1^+$ (Ref. 9)

| Final State | Possible $q\bar{q}$, L=2 $J^{PC}$ | | |
|---|---|---|---|
| | $1^{--}$ | $2^{--}$ | $3^{--}$ |
| $\pi^o\pi^+$ | $\ell$=1 | No | $\ell$=3: g meson |
| $\omega\pi^+$ | $\ell$=1 | $\ell$=1, 3 | $\ell$=3: g meson |
| $\rho^o\rho^+$ | Two $\ell$=1; $\ell$=3 | $\ell$=1, 3 | $\ell$=1; Two $\ell$=3 |
| $(A_2\pi)^+$ | $\ell$=2 | $\ell$=0, 2, 4 | $\ell$=2, 4 |

(c). $\rho^o\rho^+$ final state. This is a difficult state to study, involving two broad resonances. The Purdue group sees only a $1\sigma$ signal.

(d). $(A_2\pi)^+$ final state. It is difficult to distinguish $(A_2 \to 3\pi)$a from $\rho\rho$. Purdue sees a 1 1/2 $\sigma$ signal.

These results fall short of sorting out the R region, but they give us an idea of the scale of effort that will be needed to study this region in counter experiments, as has been proposed.

6. Study of the $A_3$

A new analysis has been performed of the reaction

$$\pi^+ p \to \pi^+\pi^-\pi^+ p \tag{14}$$

at 13 GeV/c.[27] It is concluded that the $A_3(1640)$ may be a resonant (rather than a Deck-type) effect, and that it may have a $\rho\pi$ mode. Both these conclusions are in disagreement with those of the Illinois group based on $\pi^-p$ data.[28]

The cuts against $\Delta^{++}$ in reaction (14) have more of an effect than in the corresponding $\pi^-p$ reaction. We suspect these may be the reason for the discrepancy.

7. Heavy K*'s

A study of 9 GeV/c $K^+d$ interactions[29] confirms the existence of a $J^P=3^-$ $K_N(1760)$ decaying to $K\pi$ and possibly other final states, and a possible $K_N(2100)$ with $J^P \geq 4$. This last state is in the right place to be the Regge recurrence of the K**(1420), and bears watching.

8. The $\rho'$ ($\sim$1500)

There are no new data here; only a polemic.[29'] The point is well taken: one must be on guard against kinematic enhancements, which are hard to eliminate in multi-body final states. The present status of various $\rho'$ experiments has been reviewed in Ref. 26; we would prefer to wait for more colliding $e^+e^-$ data.

9. Low-energy $\bar{p}p$ interactions

The recent measurement of low-energy total cross sections at Brookhaven[30] has turned up a number of interesting effects. One of them is a bump whose width is comparable to experimental resolution in $\sigma_T(\bar{p}p)$ and $\sigma_T(\bar{p}d)$ at the mass of the "S(1929)" meson first reported in missing-mass studies.[31] This comes at a time when missing-mass experiments seem to have abandoned the very narrow S.[32]

At higher masses, there have been new measurements of differential cross sections for $\bar{p}p \rightarrow \pi^+\pi^-$,[33] and $\bar{p}p \rightarrow K^+K^-$ [34] between 0.8 and 2.4 GeV/c. Structure is seen in $d\sigma/d\Omega$, but it does not change rapidly with increasing laboratory momentum. Partial-wave analyses await polarized target asymmetry data, forthcoming in the next year or two. Meanwhile one can make no statements about resonances in these channels.

Some other aspects of heavy mesons have been reviewed here, notably in the "T" ($\sim$2200 MeV) and "U" ($\sim$2385 MeV) regions.[35]

## BARYONS

Table VII shows some new aspects of baryon resonance physics.

1. $\Delta$ residue calculation

The phases of residues will be of some interest when we come to discuss inelastic processes like $\pi N \rightarrow \pi\Delta$, where these phases are sometimes extracted from K-matrix fits. An example based on the first resonant particle ever discovered, the $\Delta(1236)$, shows that phases of pole residues can be misleading unless interpreted properly.[36]

One can use accurate $\pi^+p$ scattering data to find the pole of the $\Delta$, obtaining[37]

$$M = 1211 - 50\,i \tag{15}$$

$$R = 53\,e^{-0.81\,i} \tag{16}$$

Table VII New baryon data

| L(qqq) | $J^P$ values | Remarks |
|---|---|---|
| 0 | $3/2^+$ | $\Delta$ residue calculation |
| | $1/2^+$ | Eventual $g_{\Sigma\Lambda\pi}$ value |
| 1 | All (also L=2) | Magnitudes and phases in $\pi N \to \pi\Delta$, $\gamma N \to \pi N$; SU(6) fits to decays |
| | $5/2^-$, others | $N\eta$ studies |
| | $1/2^-$ | $\Sigma\eta$ near threshold |
| 2 | All (also L=1) | $\pi N$ charge exchange: new forward dispersion relation calculation; new polarization |
| | All (also L=1) | New $\bar{K}N$ phase shift analysis |
| Other effects, $J^P$ uncertain | | No diffractive $\Sigma^- \to \Lambda\pi^-$ resonances |
| | | $\sigma_T$ ($K^-n$): bump at 1580 |
| | | $\sigma_T$ (KN): $Z_0^*$ ($\sim$ 1800)? |
| | | $K^+P$: $Z_1^*$ ($\sim$ 1900) uncertain |

One's initial expectation might be that the residue R should be real. This is not the case. When one includes the effects of unitarity, analyticity, the $p^3$ (p-wave) threshold factor, the correct kinematics at zero total energy, and some other reasonable dynamical assumptions, one obtains a residue which is almost exactly Eq. (16).

The threshold factor itself provides more than enough deviation from a real residue. This factor would be present if we interpreted the $\Delta$ as an "elementary" spin-3/2 particle (with complex mass) coupled to the $\pi N$ system. In such a case the coupling constant of this particle would be considerably more real than one would suppose from Eq. (16).

## 2. Resonant $\pi N \to \pi\Delta$ amplitudes

A massive analysis of $\pi N \to \pi\Delta$ in the range 1.3 GeV $\leq E_{CM} \leq$ 2 GeV is now nearing completion.[38,39] Many resonances are seen quite clearly decaying into $\pi\Delta$. The magnitudes and phases of resonant amplitudes can be compared with predictions of the single-quark selection rule models mentioned above.[10-14,40-42] Basically, this works because the N and $\Delta$ are in the same $SU(6)_W$ multiplet. Hence, the phases of resonant amplitudes in

$\pi N \rightarrow \pi\Delta$ are related in a known way to those in elastic $\pi N$ scattering whose imaginary parts must be positive, by the optical theorem. The process $\pi N \rightarrow \pi\Delta$ is an example of an "SU(3)-inelastic" reaction,[43] since it is not related to elastic scattering via SU(3).

Some resulting Argand circles are shown in Fig. 4, along with magnitudes of resonant amplitudes. In a combination like "PP11", the first letter refers to the incident ($\pi N$) orbital angular momentum, the second to the $\pi\Delta$ orbital angular momentum, the first number to 2I, and the second to 2J.

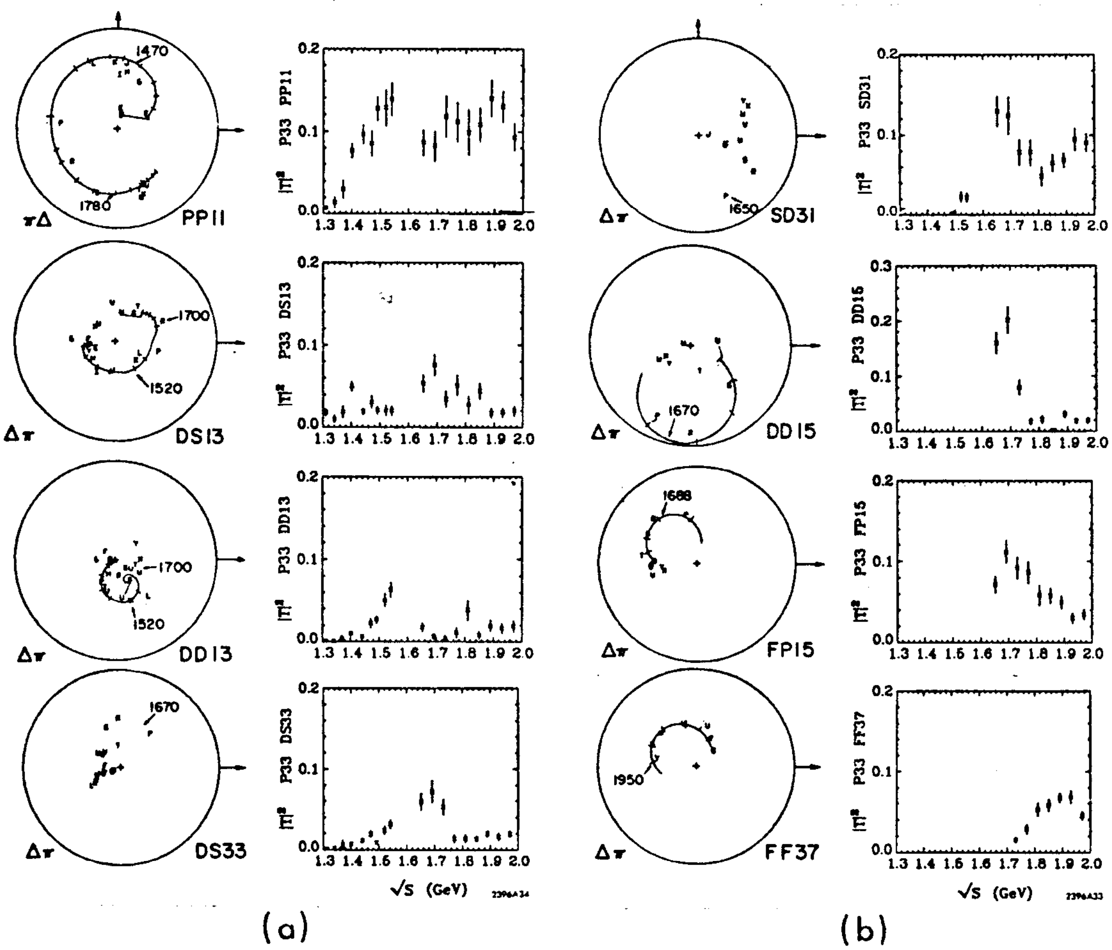


FIG. 4--(a,b) $\pi N \rightarrow \pi\Delta$ amplitudes, Ref. 38.

One notices that the imaginary parts of resonant amplitudes seem to have well-defined phases: positive or negative. One also notes (on the right-hand side of the figures) rather well-defined bumps, except in the region of a gap between 1540 and 1650 MeV.

The authors of Ref. 38 bridge the gap by demanding continuity of the PP11 wave (the first in Fig. 4). Two resonances appear in this wave: one above and one below the gap. The relative phase of amplitudes below and above the gap thus hangs on this rather slender thread.

It would of course be better to use data in the gap. These data exist, but are the subject of private smaller-scale analyses whose results should be available within the next year.

Figure 5 shows the phases of the 1972 solution[38] along with symmetry predictions. The arrows denote predicted phases in the Argand diagram, referred to a baryon-first isospin convention. [The phases in Fig. 4 refer to the isospin convention $\pi N \to \Delta\pi$, and thus have reversed relative $I = 1/2 - I = 3/2$ phase.] The crosses are the experimental phases in the baryon-first convention.

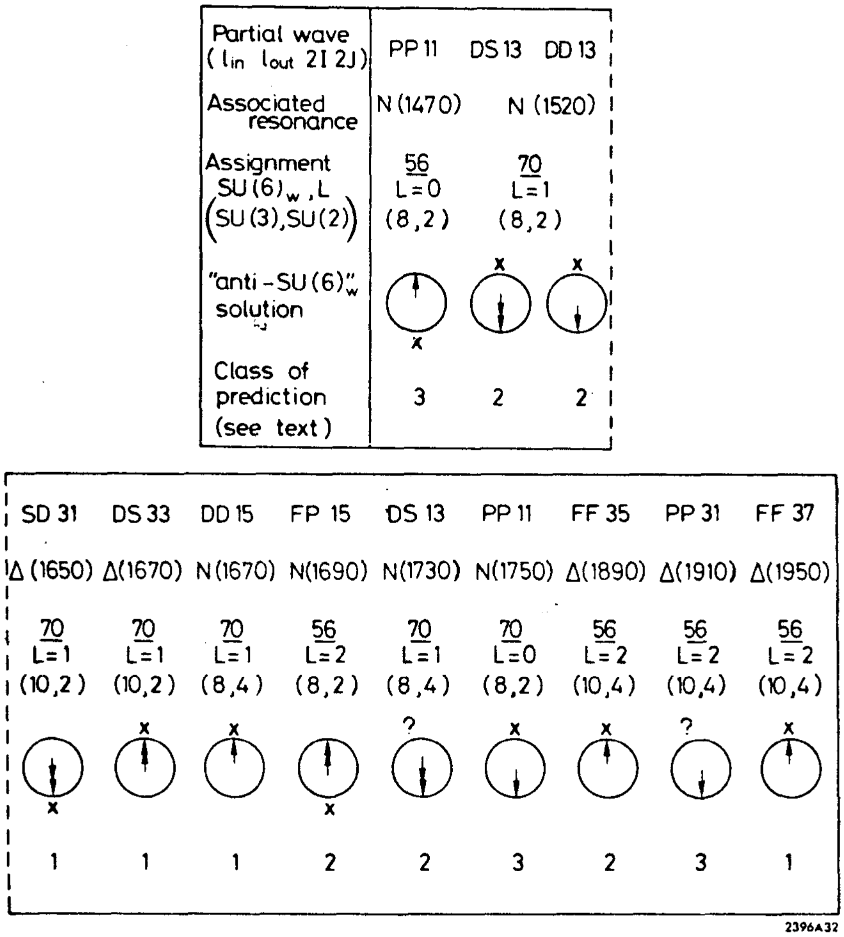


FIG. 5--Comparison of predicted resonant phases in $\pi N \to \pi\Delta$ (arrows, from Ref. 42) with experiment (crosses, from Ref. 30). Baryon-first isospin convention used here.

A double-headed arrow in Fig. 5 indicates a phase which is sensitive to which value of $\Delta L_z$ dominates: $\Delta L_z = 0$ (the "SU(6)$_W$" solution), or $\Delta L_z = \pm 1$ (the "anti-SU(6)$_W$" solution). For definiteness, we have shown the "anti-SU(6)$_W$" solution. The names stem from the relative phases of D/S and F/P waves: those of SU(6)$_W$ when $\Delta L_z = 0$ dominates, and opposite to those of SU(6)$_W$ when $\Delta L_z = \pm 1$ dominates.[40,41]

The figure is cut in two at the gap.

The phases are defined with respect to the prominent FF37 resonance.[38,44] One then sees that, above the gap, all of the "first-class predictions" hold that would be expected if $\Delta L_z = \pm 1$ dominated for 70, L=1 decays. (A "first-class prediction" is one that cannot be affected by mixing. A second-class prediction is one for which mixing can occur but is thought to be understood and does not change the predictions for unmixed states.[45,46] A third-class prediction is one where the assignment is based on an educated guess.)

In fact, $\Delta L_z = \pm 1$ is expected to dominate in certain "realistic-quark" models based on harmonic oscillator wavefunctions,[47,48] both for 70, L=1 and for 56, L=2 decays. In the case of the latter, however, we see that $\Delta L_z = 0$ seems to dominate.[49]

The disagreements above the gap in PP11 and PP31 are both for states to whose assignments we are not committed firmly at present. Apparently our estimate of the experimental DS13 situation[42] was incorrect, and the data actually agree with our prediction.[39] (This is one case in which the phase is not too well defined, since there are two overlapping DS13 resonances.) Hence one can be rather pleased with the overall pattern above the gap.

Below the gap, however, the disagreement is complete, leading one to suspect the continuation. At the urging of D. Faiman after the Purdue Conference in May, a new continuation was sought, and seems to have been obtained, in which the relative phase across the gap has changed and is now in accord with theory.[50] The situation has changed often enough that a little patience is probably in order untill things settle down. (At one point, Faiman and I had our isospin conventions wrong!) Nonetheless, the situation looks very encouraging at present.

Analyses of $\pi N \to \rho N$ and $\pi N \to \epsilon N$ are also contained in Ref. 38. There may be some disagreement with the quark model in $\pi N \to \rho N$;[48] this should also apply, in principle, to the approach of Refs. 42 and 51, through the predictions still have not been worked out in full. The Melosh approach[12-15] makes no predictions for this reaction without additional assumptions. A different analysis of $\pi^+ p \to \pi\pi N$,[44] sees very little evidence for resonant $\rho$ production, in contrast to Ref. 38, and ascribes the large $\rho$ signal to one-pion exchange. Hence results of this channel should be treated with some caution.

## 3. Resonances in $\gamma N \to \pi N$

A large-scale analysis of single-pion photoproduction in the resonance region has recently been carried out.[52] This analysis leads to resonant phases (and approximate magnitudes) which agree with quark model predictions.[47,53]

A less predictive (and more general) discussion of resonant phases in $\gamma N \to \pi N$ may be founded on the Melosh transformation.[54,55] Here one needs the transformation properties of the dipole operator $D_+$ which induces electromagnetic transitions.

The analysis of Gilman and Karliner[54] assumes the dipole operator to transform as a sum of

$$\begin{aligned} &\underline{35}, (8,3)_{W_z = \pm 1}, \quad \Delta L_z = 0 \\ + &\underline{35}, (8,1)_{W_z = 0}, \quad \Delta L_z = \pm 1 \\ + &\underline{35}, (8,3)_{W_z = \mp 1}, \quad \Delta L_z = \pm 2 \end{aligned} \tag{17}$$

A term also seems to be present which transforms as[55]

$$\underline{35}, (8,3)_{W_z = 0}, \quad \Delta L_z = \pm 1 . \tag{18}$$

This term is required in the model of Ref. 51 as well.

By neglecting the term (18) and the last term in (17), one obtains vertices for electromagnetic transitions which have the same algebraic structure as the quark model.[47,53] There seems to be no compelling phenomenological need for the other terms at present. Based on the first two terms in Eq. (17), one can predict the signs of the resonant amplitudes in $\gamma N \to \pi N$. The results are shown in Fig. 6.

From Fig. 6 one sees that all the significant signs are in agreement with the theoretical expectations of Ref. 54. Moreover, the sign of the contribution of the S-wave $\pi N$ resonance $\Delta(1610, 1/2^-)$ is that expected if $\Delta L_z = \pm 1$ dominates in $\underline{70}$, L=1 pionic decays, as suggested by the $\pi N \to \pi\Delta$ case. Occasional discrepancies can almost certainly be traced to oversimplified (unmixed) assignments. Now, one will have to await quantitative comparisons, which are forthcoming. Since the algebraic structure is the same as the quark model, which does not fare too badly, one can expect reasonable agreement; the question is whether the agreement will be significantly better.

4. SU(6) fits to decays

In the past couple of years there have been several fits to baryonic decays,[13,14,40,41,45,56] based on the algebraic structure suggested by the Melosh transformation.[15] (Some of these fits guessed the structure ahead of time.) The most recent of these[56] attempts to fit the decays of $\underline{70}$, L=1 members whose intramultiplet mixing is specified by diagonalizing mass matrices.

The agreement is not spectacular, indicating that the process of decay or mixing (or both) is not understood. We would tend to suspect the mixing assumptions. Quark model states with the same $J^P$ are likely to mix via shared physical intermediate states. These have different effects in every case (since even their masses break SU(3)), and it may be risky to expect a few well-chosen mass operators (essentially quark spin-spin and spin-orbit terms, quark masses, etc.) to describe the mixing fully.

One point on which all the analyses agree is the likely existence of low-spin hyperon resonances coupling weakly to $\bar{K}N$ and much more strongly to $\Sigma\pi$ and $\Lambda\pi$. Perhaps studies of $\Sigma\pi$ scattering in hyperon beams will help.

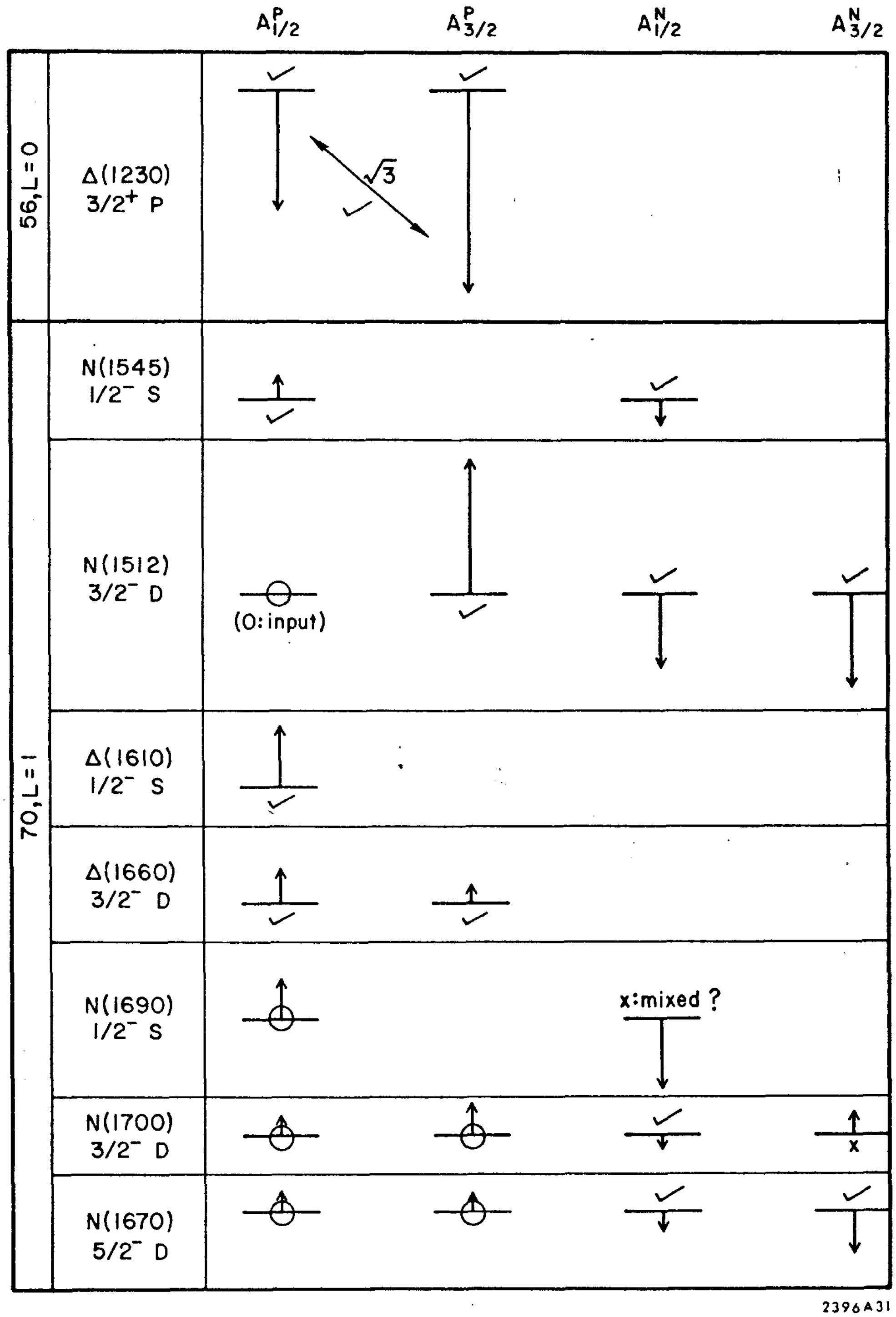


FIG. 6--(a) Resonant photoproduction amplitudes[51] compared with predicted signs.[53]

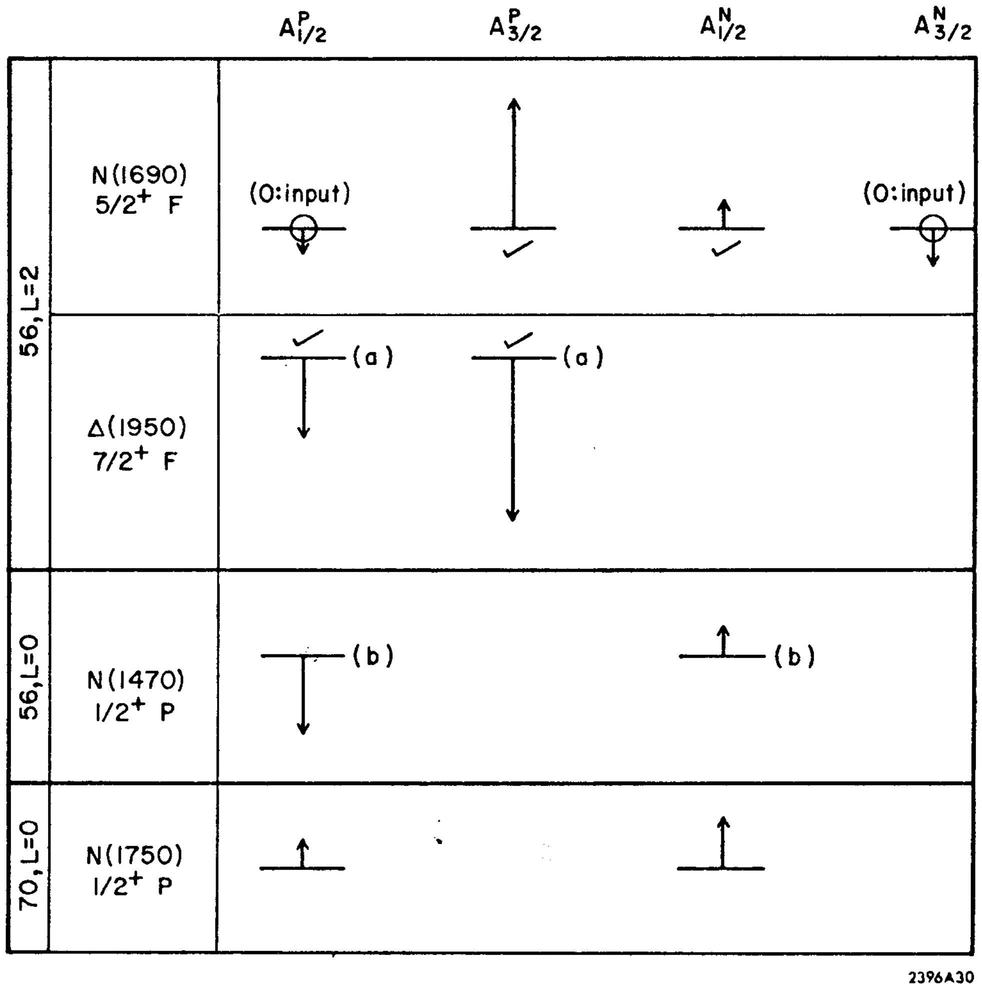


FIG. 6--(b) Resonant photoproduction amplitudes[52] compared with predicted signs.[54] Check marks denote agreement, crosses denote disagreement, 0 denotes an amplitude predicted to vanish. Normalization is such that $\Gamma(\text{Res.} \rightarrow N\gamma) \sim (A_{1/2})^2 + (A_{3/2})^2$. (a) Estimated from real part. (b) Causes trouble for the quark model. (See Refs. 52, 53.)

## 5. N$\eta$ studies

Careful measurements of the differential cross section for $\pi N \rightarrow \eta N$ have been made in the region of the N(1670, 5/2$^-$)[57] and at lower energy.[58] There may be some evidence for the decay of a high-spin resonance around 1670 MeV (5/2$^-$ or 5/2$^+$) into N$\eta$. Polarization data are needed (and will be forthcoming from the Rutherford Laboratory) before a phase shift analysis can be undertaken.

## 6. $\Sigma\eta$ near threshold

In a study of the reaction $K^-p \rightarrow \Sigma\eta$ near threshold,[59] based on a Chicago-Berkeley bubble chamber exposure, it was found that the $\Sigma$(1750, 1/2$^-$)

had an appreciable $\Sigma\eta$ branching ratio:

$$\sqrt{x_{NK} x_{\Sigma\eta}} = \pm(0.23 \pm 0.01) \tag{19}$$

This number will be an important constraint on models for mixing the three $\Sigma(1/2^-)$ states expected in the quark model. However, partly as a result of indeterminacy in the $\bar{K}N$ channel, the $\Sigma(1/2^-)$ states remain somewhat of a mystery.[45]

7. πN charge exchange

(a). Forward dispersion relations. At Batavia it was mentioned[60] that a new measurement of the differential cross section for $\pi^- p \rightarrow \pi^0 n$ disagreed with forward dispersion relations.[61, 62]

Recently a new calculation of the real part of forward πN amplitudes has appeared.[63] The real part is substantially lower, improving the agreement with the new measurements. The calculation is performed using two subtractions, which emphasizes the contribution of the low-energy regime in contrast to the approach of Ref. 62.

(b). Polarization measurements. A Berkeley group[64] has measured πN polarization at 1030, 1245, 1440, 1590 and 1790 MeV/c. Preliminary values agree well with phase shift solutions of both CERN[65] and Saclay[66] at the lowest three energies. This is reassuring since the polarization predictions of the two solutions agree with each other in this range. At higher energies some deviation sets in, especially from the CERN solution at 1790 MeV where the disagreement is quite severe. (Problems with the CERN analysis at this energy were already shown by the new differential cross section data.)[60, 61]

On the basis of the new charge-exchange measurements, we can certainly expect some refinement of nonstrange baryon resonance parameters around m = 2 GeV in the next year or two.

8. New $\bar{K}N$ phase shift analysis

Preliminary results of an analysis by the UC-LBL group of $\bar{K}N \rightarrow (\bar{K}N, \pi\Sigma, \pi\Lambda)$ were quoted at Batavia.[60] At this conference more recent results were presented in the range $1.7\ \mathrm{GeV} \leq E_{CM} \leq 1.9\ \mathrm{GeV}$.[67] The standard resonances[7] were well-fit, as well as some less well-established effects which have appeared before from time to time.[7] These are shown in Table VIII. The $\Lambda(1890, 3/2^+)$ could conceivably be an SU(3) partner of the $N(1890, 3/2^+)$, though the quark model suggests other $\Lambda(3/2^+)$ states as well in this mass range. There is some question whether one or two $\Sigma(1/2^-)$ states exist around 1720 MeV. The parameters of the $\Lambda(1750, 1/2^+)$ vary considerably among different analyses.[7]

9. $\Sigma^- \rightarrow \Lambda\pi^-$ dissociation

A group working with a 20 GeV/c $\Sigma^-$ beam at BNL[68] has studied

$$\Sigma^- + (\text{nucleus}) \rightarrow \Lambda\pi^- + (\text{nucleus}) \tag{20}$$

Table VIII "New" hyperon resonances (Ref. 67)

| | | |
|---|---|---|
| $\Lambda(1890, 3/2^+)$ | $x_{N\bar{K}} = .23 \pm .05$<br>$\sqrt{x_{N\bar{K}} x_{\pi\Sigma}} \leq .04$ | $\Gamma = 80 \pm 10$ MeV |
| $\Sigma(1720, 1750, 1/2^-)$ | $x_{N\bar{K}} \lesssim .1$ | $\Gamma \simeq 65$ MeV |
| $\Lambda(1750, 1/2^+)$ | $\sqrt{x_{N\bar{K}} x_{\Sigma\pi}} \simeq -.11$;<br>$x_{N\bar{K}}$ small | $\Gamma \simeq 50$ MeV |

and finds no evidence for diffractively produced resonances up to 1.6 GeV in mass.

On the other hand, if the process (20) is described by a Deck-type mechanism, in which the $\Sigma$ first dissociates into $\Lambda\pi$ and the pion then scatters the nucleus, one has a source of the $\Sigma\Lambda\pi$ coupling constant, to compare with the $NN\pi$, $N\Lambda K$, and $N\Sigma K$ constants via SU(3). Analyses are in progress to determine the $\Sigma\Lambda\pi$ coupling.

## 10. $\bar{K}N$ and KN total cross sections; $K^+p$ analysis

The BNL group[30] finds evidence for a bump in $\sigma_T(K^-n)$, $m \simeq 1580$ MeV, $x \simeq .1$, width narrower than experimental resolution (30 MeV). Phase shift analyses in this region are very spotty,[69] so the effect could indeed be a new resonance. Its narrowness is puzzling. However, if it were the SU(3) partner of the Roper resonance $N(1470, 1/2^+)$, belonging to a $\underline{56}$, L=0 multiplet (so that f/d = 2/3), one predicts its dominant decay modes to be $\Sigma\pi$ and $\Lambda\pi$ (not $\bar{K}N$), and its total width to be only about 25 MeV.

The KN total cross sections also have been remeasured.[30] In the interesting[60] I=0 channel, they display a broad, elastic bump around 1800 MeV, with $\Gamma \simeq 600$ MeV, probably corresponding to a $P_{1/2}$ or $S_{1/2}$ resonance. Final interpretation of this effect as a genuine $Z_o{}^*$ resonance will have to await KN charge-exchange polarization measurements at the energy in question.[60]

In the I=1 KN channel, a new measurement has been made[70] of backward $K^+p$ scattering between 1 and 1.5 GeV/c, and a new partial-wave analysis performed.[71] No partial wave need be resonant in this new analysis; the behavior of the $P_{3/2}$ partial wave is explicable purely in terms of the opening of the (nonresonant) $K\Delta$ channel.

## 11. Resonances that need attention

We conclude this section in a theoretical vein by noting those resonances not discussed here which might have been, since they are important.

(a). $N(1730, 3/2^-)$. This state is the last (of 7) nonstrange baryons to be discovered in the $\underline{70}$, L=1 multiplet. It was seen weakly in elastic $\pi N$

scattering,[66] strongly in $\pi N \rightarrow \pi\Delta$,[38] and also in one of two $\pi N \rightarrow K\Sigma$ solutions.[72] Its substantial inelasticity was expected on the basis of SU(6);[41,45] this was what made it so hard to find.

(b). N(~ 2000, 7/2$^+$). This state has been on the verge of being established for several years. Both recent $\pi N$ phase shift analyses see it,[65,66] but we have seen that some adjustments around 2 GeV are necessary. The resonance would belong to a 70, L=2 multiplet, whose existence is important for the quark model[73] and duality.[46,74,75]

(c). $\Delta$(~2200, 9/2$^-$). This is a resonance important for the quark model and duality (a 56, L=3 candidate).[46,73-75] We should start seeing it soon.

## THEORY

The selection rules and intensities characterizing hadronic transitions are being mapped out in an encouraging way. We have various languages in which to interpret these rules. The most recent is that suggested by the work of Melosh,[15] but other approaches — notably the quark model[47,48] and the so-called $^3P_0$ quark-pair-creation picture[10,11,40] — serve as useful complements and guides to the intuition. The theories are different, and it is useful to see how.[76]

The "relativistic" quark model[47,48] describes pion or photon emission in terms of a transition operator evaluated between specific wavefunctions, which are usually taken to be those of a harmonic oscillator.[73] These wavefunctions specify the problem completely: one thus obtains relations among decays involving different SU(6) multiplets, and relations between $\Delta L_Z=0$ and $\Delta L_Z = \pm 1$ pionic transitions.

The quark-pair-creation picture bears some relation to duality graphs.[77,78] The apparent connectedness of quark graphs in SU(3)[1,79] encourages us to draw similar graphs in which the quarks carry spin. When a hadron decays, some of its quarks end up in one hadron and some in the other. To conserve triality, an additional $q\bar{q}$ pair must be produced, each member of which ends up in one of the final hadrons.[11] One can imagine such a picture following from certain dual models, in which the "string" of which hadrons are assumed to be made is really an infinite number of virtual $q\bar{q}$ pairs. The "breaking" of the string between one such pair would then correspond to this model for decays.

The $^3P_0$ picture has sometimes been referred to as "$\ell$-broken SU(6)$_W$", though it is now clear that it is somewhat more general.[80] In this picture, the amplitudes corresponding to $L_Z = \pm 1$ and $L_Z = 0$ of the $q\bar{q}$ pair are left free with respect to one another, so that the term "$^3P_0$" is somewhat of a misnomer. A covariant formulation of the picture exists.[10] The relative freedom of $L_Z = \pm 1$ and $L_Z = 0$ amplitudes is the source of "$\ell$-breaking."[40]

The "current-quark" approach is based on the observation[81] that the quarks by which one realizes current algebra[82] and those composing a hadron ($q\bar{q}$ for a meson, qqq for a baryon) are not necessarily the same.[83] The two types of quarks lead to inequivalent algebrae of SU(6)$_W$.[84] In one algebra, that of "current" quarks, the currents and charges have simple transformation properties, and the states are complicated mixtures of representations.[85] In the other, it is the states which are pure representations.

A transformation V connects the two languages; it is the study of the properties and effects of V in the free quark model[15] that has led to numerous successful applications.[12-14,54,55,80]

As an example, let us consider the evaluation of a pionic decay. The decay amplitude for $A \to B\pi$ is related via PCAC[86] to the matrix element of the axial charge $Q_5$:

$$M(A \to B\pi) \sim (m_A^2 - m_B^2) \langle B | Q_5 | A \rangle \, . \tag{21}$$

The evaluation of $\langle B | Q_5 | A \rangle$ was difficult until recently. In the "current-quark" representation, $Q_5$ transforms simply, i.e.,

$$Q_5 \sim \underline{35},\ (8,3)_{W_z=0}\,,\quad L_z = 0\,, \tag{22}$$

in $SU(6)_W$. (Here and in Eqs. (17) and (18), the numbers in parentheses refer to SU(3) and $SU(2)_W$ dimensions, respectively.) On the other hand, as mentioned, A and B are mixed states. It was fashionable at one time to construct models for the mixing.[85] Now, however, by assuming that there is a transformation V converting the states A and B to <u>pure</u> current-quark representations:

$$|\widetilde{A}\rangle_{(\mathrm{pure})} = V |A\rangle_{(\mathrm{mixed})}\,, \tag{23}$$

one can cast the complexity onto the operators:

$$\begin{aligned} \langle B | Q_5 | A \rangle &= \langle \widetilde{B} | V\, Q_5\, V^{-1} | \widetilde{A} \rangle \\ &\equiv \langle \widetilde{B} | \widetilde{Q}_5 | \widetilde{A} \rangle \end{aligned} \tag{24}$$

where it remains to find the properties of the transformed operator

$$\widetilde{Q}_5 = V Q_5 V^{-1} \tag{25}$$

In the free quark model, the properties of $\widetilde{Q}_5$ are remarkably simple:[15]

$$\begin{aligned} \widetilde{Q}_5 \sim\ & \underline{35},\ (8,3)_{W_z = 0}\,, \quad L_z = 0 \\ +\ & \underline{35},\ (8,3)_{W_z = \mp 1}\,, \quad L_z = \pm 1 \end{aligned} \tag{26}$$

One sees in Eq. (26) the $\Delta L_z = 0$ and $\Delta L_z = \pm 1$ pieces to which we have referred earlier. Their matrix elements between any pair of multiplets are free parameters. The second piece may be thought of as an effect of transverse motion of quarks.

It has been shown[80] that the $^3P_0$ picture leads to precisely the same rules as Eq. (26) for pionic transitions. An important difference is that, while the kinematic factor in the $^3P_0$ picture is indeterminate, and is thus usually taken to be Eq. (7), the PCAC hypothesis (21) leads to the unique factor in Eq. (8). (Equation (21) arises when $Q_5$ is evaluated between infinite-momentum states, so one's intuition regarding the need for conventional centrifugal barriers such as (7) may fail.)

Numerically, there is not much basis for distinction between Eqs. (7) and (8) as yet: We have mentioned that S-wave meson decays fare better with Eq. (8), as does the relation between $f_0 \to \pi\pi$ and $A_2 \to \rho\pi$.[13] On the other hand, certain baryon decays become better with Eq. (7).[13,40,41]

Some further comparisons among the various models are discussed by Kugler.[76] Whatever the language, it is clear that we now have a whole new set of symmetry predictions for hadronic three-point functions which are worthy of experimental tests. This is because recent efforts have striven toward symmetries lower than $SU(6)_W$ (which would, for example, keep only the first term in Eq. (26)). As we have seen from the $B \to \omega\pi$ example, $SU(6)_W$ does not work.

If the symmetries discussed here are ever ruled out by the data, there is a "rear-guard" set of $SU(3) \times SU(3)$ symmetries to which one can retreat[12,87] before being beaten back to SU(3). At the moment, such a retreat seems unnecessary, but we invite our colleagues to try to force us back!

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85. See, e.g., H. Harari, Phys. Rev. Letters 16, 964 (1966); ibid., 17, 56 (1966); G. Altarelli, R. Gatto, L. Maiani and G. Preparata, Phys. Rev. Letters 16, 918 (1966); I. S. Gerstein and B. W. Lee, Phys. Rev. Letters 16, 1060 (1966); D. Horn, Phys. Rev. Letters 17, 778 (1966); F. Gilman and H. Harari, Phys. Rev. 165, 1803 (1968); F. Buccella, et al., Nuovo Cimento 69 A, 133 (1970) and Ref. 49.

86. A good discussion is given by Horn, Ref. 85. The matrix element is evaluated in the infinite-momentum frame.

87. J. L. Rosner, Phys. Rev. D 6, 1781 (1972).