D. $\bar{K}N$ Phase Shifts

The hyperons are much less well mapped out than nonstrange baryons. Low-energy K^- beams are not very intense, and the identification of specific hyperons with given symmetry multiplets is harder (see sections III and V). A Λ can belong to an SU(3) octet or singlet, and a Σ to an octet or decimet. Mixing can occur and usually does. Then why study hyperons at all? Couldn't we be content with the quark model and related schemes as applied only to nonstrange particles?

Hyperons are important for several reasons (see section III.B.1d). First, we would like to know how far SU(3) can be pushed. Perhaps it holds only for a subset of the observed resonances (Meyer, 1971). Second, given SU(3), we can learn about f/d ratios (hence about SU(6), which predicts them) and about mixing effects (not satisfactorily understood at present). The fact that so many SU(3) multiplets are incomplete may cause some concern, though (in my opinion) it follows primarily from the difficulties in obtaining solid information about the hyperons at present.

Recent analyses of the $\bar{K}N$ system* are quoted by (Lovelace, 1972): they include publications by (Langbein, 1972) and (Lea, 1973).** Another analysis has been performed by (Merrill, 1973) of LBL-Chicago K^-p bubble chamber data between $E_{c.m.}$ of roughly 1.7 and 1.9 GeV. This analysis incorporates other data, of course. A compilation of $\bar{K}N$ data (Wagner, 1971b) on tape is available from the Particle Data Group (Kelly, 1973). In contrast to the πN case, much of this is still based on bubble chamber exposures. These have

*(Lasinski, 1972).

**See also the recent review by (Plane, 1973).

been discussed by (Ferro-Luzzi, 1971a; Lasinski, 1972), (Tripp, 1971) (dealing with details at low energy), and (Tripp, 1973). Bubble chamber $\bar{K}N$ exposures have no important energy gaps; the technique has probably been pushed to its limit with regard to hyperon physics, with the exception of $K_L^o p$ interactions (mentioned below).

The study of $\bar{K}N \rightarrow$ resonances using counters has large gaps. These have been pointed out by (Tripp, 1973). The hardest experiments are at lowest energies, where K^- fluxes are lowest. An important remaining gap is low energy $K^- p \rightarrow \bar{K}^o n$.

Figure 13 shows the pattern of expected hyperons that haven't yet been seen:

At $E_{c.m.} \simeq 1.6$ GeV/c^2 ($p_L^K = 0.6$ GeV/c^2) Λ and Σ, $1/2^+$ octet partners of the Roper resonance

Several negative-parity resonances between $E_{c.m.} = 1.8$ and 1.9 GeV/c^2 (1 GeV/c $< p_L^K <$ 1.25 GeV/c)

Various positive-parity states above $E_{c.m.} = 1.9$ GeV/c^2 ($p_L^K \geq 1.25$ GeV/c)

A $\Lambda(7/2^+)$ (m $\simeq$ 2020 MeV: Barbaro-Galtieri, 1970b) in need of confirmation.

The confirmation of Roper resonance SU(3) partners is crucial to our understanding of the limitations of SU(3). If we classify the Roper resonance into <u>56</u>, L=0, as a "radial" excitation of the nucleon (see, e.g., Dalitz, 1966b), then $SU(6)_W$ (section VI) predicts that the couplings of its associated octet should be characterized by $f/d = 2/3$. The unseen negative-parity Λ's and Σ's are likely to be mixtures of states within the $\underline{70}$, L=1 multiplet (Faiman, 1972). The classification of the higher positive-parity unseen states may be difficult unless mixing is understood better. The study of specific low-spin hyperon resonances above $E_{c.m.} = 1.9$ GeV/c^2 is thus likely to be rather unfruitful at the present level of data.

The interesting questions about hyperons thus refer to missing low-mass states and new properties of observed states (at higher mass, these tend to have higher spin and unique quark model assignment). We list some topics of interest below.

1. SU(3) and $SU(6)_W$ preliminaries

As inelastic channels play a more important role in the study of hyperons than in the case of nonstrange resonances, it is useful to have a table of SU(3) expectations for ratios of partial widths. Table D.1 shows the various channels and the expected SU(6) $\times$ SU(3) factors for unmixed quark model states. The signs are those of the coupling to the given final state.

There are enormous variations from multiplet to multiplet of the ratios in Table D.1. The most dramatic of these come from the fact that the $\bar{K}N$ coupling is expected to vanish exactly for one of the Λ states, and is strongly suppressed for two of the Σ's (it would vanish when $f/d = 1$). This indicates that certain unmixed resonances may be most prominent in inelastic channels such as $\bar{K}N \rightarrow \Lambda\pi$ or $\Sigma\pi$. Moreover, certain mixed resonances can be prominent in channels such as $\Lambda\eta$ (Petersen, 1972), though this is not directly evident from Table D.1.

2. Inelastic $\bar{K}N$ states

There are a number of these expected. The examples listed below show the importance of refining elastic $\bar{K}N$ phase shifts as well as learning about inelastic ones.

a. $\Lambda(1830, 5/2^-)$. According to the quark model, this state has quark spin 3/2 and should decouple altogether from $\bar{K}N$. (A simple argument is given by Lipkin, 1969b.) Various weaker schemes (section VI) agree. Experimental analyses agree that x_{el} is small but there is wide variation in the quoted values (.03 ± .02 to .10 ± .03; see Lasinski, 1973). Since the state is seen, the selection rule clearly can't be exact, but one would like a better idea of just how good it is.

b. $\Lambda(2020, 7/2^+)$. This state is needed in the quark model (Faiman, 1971) and for duality (Rosner, 1973a). It is another assigned to $S_q=3/2$ and hence expected to have zero $\bar{K}N$ coupling. It is most prominent in one analysis of $\bar{K}N$ (Barbaro-Galtieri, 1970b), with $\sqrt{x_{N\bar{K}} x_{\Sigma\pi}} \simeq 0.15$. Since $x_{\Sigma\pi} < 1$ this requires $x_{N\bar{K}} \gtrsim 0.04$, so the state should be visible in precise analyses of the elastic channel. The state should be confirmed; it is one of two unique members of the whole $\underline{70}$, L=2 multiplet. The other is $N(\sim 2025, 7/2^+)$; see Fig. 37b and Table XXV.

c. Low-lying $\Sigma(1/2^+)$: Roper partner. The conventional assignment of the Roper resonance $N(1470,\ 1/2^+)$ is to a $\underline{56}$ (8,2), L=0. The corresponding Σ member should have weak $\bar{K}N$ coupling, stronger $\Lambda\pi$ coupling, and strongest $\Sigma\pi$ coupling. Its mass should lie around 1600 MeV; the Particle Data Group compilation quotes a candidate in need of confirmation (Lasinski, 1973). The elastic width of such a resonance is of considerable importance since it sets the scale of the inelastic ones.

Recently a measurement of $\sigma_T(\bar{K}N)$ (Carroll, 1973b) has observed a bump at 1580 MeV in the I=1 channel.* This bump is rather inelastic: $(J+1/2)x \simeq .1$. Its total width is less than experimental resolution (around 30 MeV).

If this state were the partner of the Roper resonance, we can calculate its expected $\Lambda\pi$ and $\Sigma\pi$ partial widths using the PCAC model of section VI. Assuming

$$\Gamma[N(1470) \to N\pi] = 115 \text{ MeV} \quad , \tag{IX.3}$$

we find

$$\Gamma[\Sigma(1580) \to \Lambda\pi] = 17 \text{ MeV} \tag{IX.4}$$

and

$$\Gamma[\Sigma(1580) \to \Sigma\pi] = 8 \text{ MeV} \quad . \tag{IX.5}$$

The $N\bar{K}$ mode cannot be estimated reliably using PCAC. However, the final c.m. 3-momenta in $\Sigma\pi$ and $N\bar{K}$ are almost the same, so that

$$\Gamma(N\bar{K})/\Gamma(\Sigma\pi) \simeq \tilde{\Gamma}(N\bar{K})/\tilde{\Gamma}(\Sigma\pi) = 1/16 \quad .$$

(See Table D.1; we have assumed $\Sigma(1580)$ to belong to $\underline{56}$ (8, 2).)

In view of this, it is astonishing that the state has been seen at all! It should be observable in hyperon-pion scattering. (See section X.B.)

*This bump has been seen before. See (Bowen, 1970).

3. Specific inelastic channels

Each channel has its advantages and disadvantages in answering interesting resonance questions.

a. $\overline{K}N \rightarrow \Lambda\pi$. This pure I=1 channel has recently been analyzed by (Van Horn, 1972), who finds many ambiguities in the amplitude. For reasons of statistics, polarized target studies — while highly desirable — will probably be impossible in the near future. On the other hand this channel can act as an important constraint when combined with others in a multi-channel analysis. For this reason counter experiments to study $d\sigma/d\Omega$ and Λ polarization at low energies would be extremely helpful. A region of particular interest is $E_{c.m.} \sim 1.5$ to 1.7 GeV ($p_L^{\overline{K}}$ = 400 to 800 MeV/c) with the intention of comparing $\Lambda\pi$ and $\Sigma\pi$ couplings to the expected Roper resonance partner in this region. (See Eqs. (IX.4) and (IX.5).)

b. $\overline{K}N \rightarrow \Sigma\pi$. The existence of both I=0 and I=1 in this channel is actually an advantage in the low-energy region, where the prominent $\Lambda(1520, 3/2^-)$ can be used as a reference amplitude. (In $\overline{K}N \rightarrow \Sigma\pi$ no such well-known reference amplitude exists.) On the other hand, the pure I=1 channel is difficult to study, and forthcoming data on $K_2^o p \rightarrow \Sigma\pi$ (see below) may prove extremely helpful. Systematic counter experiments on $K^- p \rightarrow \Sigma^{\pm}\pi^{\mp}$ are needed in the low-energy region, with detection of Σ polarization. One of the crucial questions is the confirmation of the suggested Roper partner mentioned above.

c. $K^-p \rightarrow \Lambda\pi\pi$. The recent analysis by (Prevost, 1973) is an important first step in testing the predictions of $SU(6)_W$ (and broken versions) set forth in section VI. A clean test of these schemes in $\bar{K}N \rightarrow \Sigma(1385)\pi$ can be performed by comparing the resonant phases of $\Sigma(1765, 5/2^-)$ and $\Sigma(2030, 7/2^+)$. Details are mentioned by (Faiman, 1973b). The (Prevost, 1973) analysis is not even consistent with SU(3) at present, but data of much higher quality (perhaps obtained by counters if at all possible) are needed before this conclusion can be taken seriously.

d. $K^-p \rightarrow \Lambda\eta$. Table D. 1 shows that unmixed Λ states in the quark model tend to have weak couplings to $\Lambda\eta$ in comparison with their $N\bar{K}$ couplings [except for $\underline{70}$ (8,4)]. On the other hand the $\Lambda(1670, 1/2^-)$ has a relatively strong $\Lambda\eta$ coupling, indicating the importance of mixing from a quark model standpoint (Petersen, 1972; Faiman, 1972). It is likely that other states coupling to $\Lambda\eta$ are also highly mixed, as the high threshold picks out high-mass, low-spin states of which there are many expected in the quark model. Precise differential cross section and Λ polarization measurements would be useful in a counter experiment between threshold and $E_{c.m.} \simeq 1.9$ GeV ($p_L^{K^-} \sim 0.7$ to 1.2 GeV/c). Such data would be extremely useful in sorting out mixing schemes for positive-parity hyperons based on the approach of (Faiman, 1972).

A recent preprint by the Saclay group (Rader, 1973) describes the results of analyzing bubble chamber experiments in $K^-p \rightarrow \Lambda\eta$. Resonant amplitudes of the $\Lambda(1827, 5/2^-)$, $\Lambda(1818, 5/2^+)$, and $\Lambda(2100, 7/2^-)$ agree with those predicted from SU(3) within very large experimental errors. As expected (section III. C. 2d), these amplitudes all are of the same sign.

e. $\underline{K^-p \to \Sigma\eta}$. This reaction is the companion to the previous one, but for I=1 states. The dominant effect in this channel is an S-wave threshold effect, $\Sigma(1750, 1/2^-)$ (Jones, 1973b). Inspection of Table D.1 shows that any resonance for which the $\Sigma\eta/\Lambda\pi$ ratio is not one times phase space and barrier factor ratios <u>must</u> be an octet-decimet mixture. As in the case of $\Lambda\eta$, this channel is thus a good one for sorting out mixing effects, which are still in considerable uncertainty for the $1/2^-$ states (Faiman, 1972).

f. $\underline{\bar{K}N \to K\Xi}$. Table D.1 shows some spectacular enhancements predict for unmixed Σ states in the quark model. This reaction involves a strong barrier suppression of higher partial waves, but somehow must build up a backward peak and no forward one by energies for which Regge pole exchange ideas begin to hold. The claim for a ΞK coupling of $\Lambda(2100, 7/2^-)$ by (Litchfield, 1971) would support this idea: high partial waves might indeed manage to survive. A trigger could probably be devised for $K^-p \to K^+ + X^-$ (S=-2 state), with $E_{c.m.}$ in the resonance region, for a multiparticle spectrometer such as Omega at CERN, MPS at Brookhaven, or LASS at SLAC. Certainly higher-momentum experiments have been contemplated (see section X.D below). The reaction $K_L^0 p \to \Xi^0 K^+$ (in a bubble chamber) is also worth a preliminary phase shift analysis.

g. $\underline{K^-p \to \Lambda\omega}$. The $\Lambda(2100, 7/2^-)$ apparently has a small $\Lambda\omega$ decay (Brandstetter, 1972). This can be used (if one believes SU(3)) to set the scale of the $\Lambda(2100)$ coupling to $\bar{K}^*N$ in $K^-p \to K^-\pi^+n$. If the apparent $\Lambda(2100)$ contribution to this latter process seems very big, one must beware of mishandled OPE contributions. While the $\Lambda\omega$ decay of Λ resonances is a powerful tool in testing symmetries and quark model assignments (see section VI. D), no clean predictions exist above $\Lambda\omega$ threshold because too many (probably mixed) states are expected.

4. Uses of $K_L^o p$ interactions

The use of K_L^o beams has several advantages. The beam is neutral, and thus keeps its momentum (usually a spread of values) without slowing down and stopping even at low energies. One can study pure Y=-1, I=1 final states without resorting to K^-d interactions and problems associated with the deuteron. Finally, some information on the Y=+1 channel can be obtained via its interference with Y=-1 in $K_L^o p \rightarrow K_S^o p$ (see below, subsection E). Specific hyperon channels of interest include the following.

a. $K_L^o p \rightarrow \pi\Sigma$. The reaction $K_L^o p \rightarrow \Sigma^o \pi^+$ has recently been found to yield a very clean sample of bubble chamber events (G. Alexander, private communication). This channel is of interest because of numerous SU(3) or SU(6) troubles with $\Sigma^* \rightarrow \Sigma\pi$ decays (they are generally too low experimentally; see, e.g., Table XVIII). Resonances of interest include $\Sigma(1765, 5/2^-)$, $\Sigma(1915, 5/2^+)$, and $\Sigma(2030, 7/2^+)$.

b. $K_L^o p \rightarrow N\bar{K}\pi$. If the $\bar{K}\Delta$ final state can be isolated here, the comparison of $\Sigma(1765, 5/2^-)$ and $\Sigma(2030, 7/2^+)$ contributions is of great interest, as in $K^-p \rightarrow \pi\Sigma(1385)$. (See above.)

5. Hyperon summary

The primary need is a systematic study of $\bar{K}N \rightarrow \bar{K}N$, $\pi\Lambda$, and $\pi\Sigma$ with counters at low energies (see Tripp, 1973). The quality of data must be improved to the point that energy-independent phase shift analyses become possible. (This will require intense low-energy K^- beams.) Only such data can constrain symmetries rather than merely confirming them. In a few cases, mentioned above, data of lower quality still can be helpful.

E. KN Phase Shifts

Any KN resonance is exotic, i.e., it cannot be made of three quarks. The present candidates (see section II) include an I=0 state, Z_0^* (~1800, probably $1/2^+$), and an I=1 Z_1^*(~1900, $3/2^+$). The latter is looking less likely lately (Kelly, 1973), but is not yet disproven. The former would be an elastic resonance. Some suggestions for learning more about these states are made by (Dowell, 1972; Lovelace, 1972; and Lasinski, 1973). We list a few of these:

1. Measurements of K^+n charge exchange polarization and elastic polarization. The former has been performed at only one energy using double scattering, while the latter is possible in principle on polarized deuterons.

2. R and A measurements in K^+p scattering. These serve two purposes.
(a) They tie down low-energy solutions, confirming or disproving Z^*'s;
(b) They help establish the diffractive mechanism setting in at higher energies.

3. <u>Counter data on K^+n elastic and K^+p inelastic channels</u>. The statistical significance of these data, based on bubble chamber exposures, could perhaps be improved using cleverly designed multiparticle spectrometers.

4. <u>$K_L^o p$ interactions</u>. The reaction $K_L^o p \rightarrow K^+ n$ has been studied at NINA (Dowell, 1972) and results should be available soon. Another possibility is the reaction $K_L^o p \rightarrow K_S^o p$, using the interference among I=1, Y=-1 and I=1, 0, Y=1 amplitudes to sort out the existence of the suggested $Z_0^*(1780, 1/2^{\pm})$.* This may require more understanding of the low partial waves in I=1 $\bar{K}N$ scattering than one has at present, and hence increases the urgency of obtaining such knowledge.

F. <u>Baryon-Antibaryon and Baryon-Baryon Channels</u>

Detailed phase shift analyses in the baryon-antibaryon system are not yet possible,** despite the existence of a number of simple two-body final states. These include $\bar{N}N \rightarrow \pi^+\pi^-$, K^+K^-, $K_S^oK_S^o$, $K_S^oK_L^o$, $\pi^o\pi^o$, $\pi^o\eta^o$, and $\eta^o\eta^o$. The real stumbling block has been the difficulty of working at low enough momentum to allow only a few partial waves to contribute. For example, polarization asymmetry in $\bar{p}p \rightarrow \pi^+\pi^-$ has been measured at 1.64 GeV/c, where a true partial-wave analysis is impossible (Ehrlich, 1972a) but no results of a proposed experiment at lower momenta are available yet (Ehrlich, 1972b). A recent British collaboration at CERN has measured $\bar{p}p \rightarrow \pi^+\pi^-$ and K^+K^- between 0.8 and 2.4 GeV/c (Parsons, 1973; Hovjat, 1973).

*This has been mentioned to me by D. Cline and by G. Alexander, though I am not aware of the origin of the suggestion.

**On the other hand, phenomenological potentials have already been constructed for the low-energy $N\bar{N}$ interaction (Bryan, 1968).

A recent review by (Lemke, 1973) may be of interest for those contemplating experiments on elastic $\bar{p}p$ scattering. The unknown region (p_L < 200 MeV/c) is extremely hard to study, but crucial.* Other aspects of $N\bar{N}$ interactions are discussed in the proceedings of the 1972 Chexbres $N\bar{N}$ Symposium, and by (Muirhead, 1973).

A few (perhaps unfeasible) suggestions can be made for experiments that could lead to detailed partial-wave analyses in the $\bar{N}N$ system.

1. <u>Low energy $\bar{n}$ beams</u>

Proposals (Cliñe, 1971) to study low energy $\bar{n}$ interactions at Argonne will avoid the embarrassing tendency of slow antiprotons to slow down further and stop. One can study $\bar{n}p$ elastic scattering; with a suitably constructed counter experiment one could also study the much rarer process $\bar{n}p \to K^+\bar{K}^o$, which would be much easier to analyze. The total $\bar{n}p$ cross section is also of great interest since a comparison of σ_T^2 and σ_{el} gives the maximum ℓ contributing to the processes (for a discussion, see Lemke, 1973).

2. <u>Diving below threshold with deuterons</u>

The momentum of the "spectator" nucleon in a deuteron can be chosen to dive below or sweep through $N\bar{N}$ threshold, as in the reaction studied by (Gray, 1971): $\bar{p}d \to p_S(MM)^-$. One could then use antiprotons of a low but relatively controllable momentum to perform all sorts of elastic and inelastic scattering experiments near $N\bar{N}$ threshold, such as $\bar{p}d \to p_S\bar{p}n$, $\bar{p}d \to n_S\bar{p}p$, $\bar{p}d \to n_S\pi^-\pi^+$. Presumably one such channel could be studied in a counter experiment with sufficient geometric acceptance to allow for a genuine

*For example, one envisions eventually being able to obtain the imaginary parts of the S- and P-wave scattering lengths as one can do in the $\bar{K}N$ system (Dalitz, 1960). This would settle once and for all the question of the absolute rate of S- and P-wave annihilations at rest.

phase shift analysis. Of course, the target nucleon would be off its mass shell, making for some question of interpretation.

3. Reaction $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ near threshold

At the lowest momentum studied, this process already shows strong forward-backward asymmetry (Button, 1961). It might be interesting to see the manner in which this develops, particularly in view of the suggestion (Rosner, 1972b) that there could be narrow resonances just above any baryon-antibaryon threshold (such as $\bar{\Lambda}\Lambda$). At the momenta of interest (p_L = 1.43 to 1.8 GeV/c) there should be no trouble in obtaining suitable antiproton beams.

4. Low-density targets

It may be possible to use $\bar{p}$'s of low but well-defined momentum in low-density targets, for instance in a streamer chamber. (R. Tripp suggested this to me.)

No convincing baryon-baryon resonances have been seen up to now, and there are no particular theoretical reasons for expecting them. Someday perhaps a partial-wave analysis of the ΛN system may become possible; if so, the behavior near ΣN threshold would be of interest (Benary, 1970). Formation experiments of this type are the only reliable way of confirming suggestions of dibaryon resonances in production experiments (Shabazian, 1973).

G. A Question List

In judging whether a new low-energy experiment in the resonance region is called for, one can use a number of criteria.

1. Is the measurement qualitatively different? Examples are R and A in πN and KN scattering. Even if phase shift analysis agree at present on predictions for such unmeasured parameters (they do in πN: Wagner, 1972b) the possibility always exists that the necessary theoretical input in such analyses was wrong.

2. Will the measurement resolve a discrete ambiguity among conflicting solutions?

3. Do reliable sets of raw data disagree with one another at the energy in question? Some reference to this is made by (Almehed, 1972) in πN scattering, for example.

4. Does the measurement permit reliable extension of existing phase shifts upwards in energy? One is particularly interested in extending elastic πN to about 2250 MeV = $E_{c.m.}$ if possible, and $\pi N \rightarrow \pi\Delta$ to about 2100 MeV. *

5. Does the measurement provide new information on inelastic channels?

6. Does the measurement facilitate low-energy amplitude analysis? An example is in K^+p scattering, where R and A measurements would help decide the nature of the diffractive process.

*These extensions are of interest in testing for new multiplets of the rest symmetry predicted by the quark model and duality; see Table XXIII.

The existence of a number of compilations of low-energy data (Kelly, 1973) makes it much easier to spot gaps than before. We have tried to indicate some of these gaps from the point of view of internal symmetries. Continual progress has been made spanning roughly two decades of direct-channel resonance studies. We can expect many further answers to questions about symmetry, duality, and the quark model with well-chosen experiments at low and intermediate beam energies.

X. HIGH-ENERGY EXPERIMENTS

Many new means of studying resonances will be available as a result of new high-energy or specialized-function accelerators and new detection techniques. Colliding electron-positron beams (subsection A) can shed a great deal of light on present theoretical questions in resonance physics. One-pion-exchange will continue to be of interest at machines of increasing energy, for the study of both mesons and baryons (subsection B). Track-sensitive targets and other devices permitting the study of final states involving more than one neutral particle are discussed in subsection C. For resonances which must be studied in production configurations, such as Ξ^*'s and most mesons, multi-particle spectrometers such as Omega at CERN, MPS at Brookhaven, and LASS at SLAC will be essential in going beyond the limitations of statistics imposed by bubble chambers. These, as well as triggered visual devices, are discussed in subsection D. Such devices are particularly helpful in studying baryon exchange. Coulomb dissociation of hadrons, easier to study at high energies, is mentioned in subsection E. Some processes depend on high energies in a fundamental way, and are noted in subsection F. Subsection G is a summary.

A. Colliding e^+e^- Beams

There are a number of colliding e^+e^- beam facilities which have recently begun operating or are scheduled in the next few years.

It was first found at ADONE (Frascati) that the cross section for $e^+e^- \to$ (hadrons) was an appreciable fraction R ($\simeq 2$) of that for $e^+e^- \to \mu^+\mu^-$ up to $E_{CM} \simeq 3$ GeV. The Cambridge Electron Accelerator storage rings have recently ended their (unfortunately short) existence with an indication that this ratio may be increasing with energy: for $E_{CM} = 5$ GeV, $R = 6.3 \pm 1.5$ (Strauch, 1973). SPEAR (at Stanford) has already seen a number of hadronic events. With all these hadrons around, what can we expect in the way of resonances ?

There are three main ways in which one expects hadron resonances to show up here: in the direct channel, in production, and in two-photon processes.

1. $e^+e^- \rightarrow$ resonances

The channel is useful only if resonances are rather broad or if the energy can be controlled closely enough to see narrow spikes.

The ρ' effect is an example of a broad resonance at the expected place, corresponding to the negative-parity group expected in a harmonic-oscillator quark model. If the parity alternation of Fig. 18 continues, with the period of ~ 2 GeV^2 in s already established, and if resonances dominate $\sigma(e^+e^- \rightarrow$ hadrons), we may see a few more wiggles (as in Fig. 19b) before the continuum sets in. The next energy at which one expects $\sigma(e^+e^- \rightarrow$ hadrons) to be enhanced - above the ρ' - is $E_{CM} \simeq 2.1$ to 2.2 GeV.

Narrow spikes in $e^+e^- \rightarrow$ hadrons (or, for that matter, in $\gamma \rightarrow$ anything) are expected in a variety of theories. Some theories of the hadrons which seek to unify the weak and electromagnetic interactions invent a fourth quark, u', (Glashow, 1970; Maki, 1964; Hara, 1964) carrying a new quantum number known as "charm". Vector mesons composed of pairs of such quarks may be expected to be quite narrow (See, e.g., Freund, 1972; Snow, 1973). They could conceivably be observed in $e^+e^- \rightarrow$ hadrons, $e^+e^- \rightarrow \mu^+\mu^-$, etc. Actually one might also observe them in $e^+e^- \rightarrow$ (narrow meson) + (something else), using the momentum of "something else" to sweep through the mass of the narrow meson. Aside from "charmed" states one might also hope to see some of the varied gauge bosons required in theories of the weak and electromagnetic interactions (see, e.g., Lee, 1973).

2. $e^+e^- \to$ resonance + something else

The e^+e^- channel is a unique "hadron-less" source of hadrons: it thus avoids many of the problems inherent in proton targets. Many effects which behave in one way when produced by pions on protons (for example, the A_1) may behave quite differently when produced in e^+e^-. Perhaps in $e^+e^- \to \pi$"A_1" we will finally be able to tell whether the A_1 is a resonance, and in $e^+e^- \to \pi B$ we may hope to check the helicity structure of the $B \to \omega\pi$ decay in a process other than $\pi p \to Bp$. Using the fact that synchrotron radiation leads to anti-parallel polarization of e^+ and e^- (after a couple of hours, at SPEAR), one has a source of virtual photons polarized linearly parallel to the magnetic field. This is a boon in studying resonance production mechanisms. Here are some of the theories at stake:

a. SU(3). Lipkin has emphasized (Lipkin, 1973d) that in the SU(3) limit the processes

$$e^+e^- \to K^o\overline{K}^o \tag{X.1}$$

$$\to K^{*o}\overline{K}^{*o} \tag{X.2}$$

are totally suppressed. Many other relations (to be mentioned below) have never been checked before.

b. SU(6). A simple set of rules for hadron pair production makes use of the model of Fig. 43a (see, e.g., Ritson, 1972). Let the virtual photon produce an S-wave $q\bar{q}$ pair, which then "dresses" itself by sucking an additional $q\bar{q}$ pair out of the vacuum. One then obtains the relations shown in

Table XXVI for processes related to pion pair production. Final states which may be easier to detect are labelled with an arrow.

In Table XXVI all final states are in a relative p-wave (a non-trivial prediction for the VV states). Borrowing from experience in resonance decays, one then expects to need a factor $\left(p_{AB}^{CM} / p_{\pi\pi}^{CM}\right)^3$ in correcting the ratios. There may be additional factors (Ritson, 1972) suppressing pair production of strange quarks in the starred cases.

c. Color non-singlets. A recent explanation of the rise in R alluded to above is that the threshold for production of a new type of state has been passed somewhere between $E_{CM} = 3$ and $E_{CM} = 5$ GeV. These states are ones which, in contrast to the lowest-lying ones, are no longer "color singlets" (see section V). Their decays to the color-singlet variety of mesons must violate "color SU(3)",* and thus should proceed slowly.

Even below "color threshold", the observed value of R = 2 implies that the outermost quarks in Fig. 43b are of all three colors, with equal probability (Gell-Mann, 1972a). How do the additional $q\bar{q}$ pairs "fill in" the space between them so as to form only color-singlet mesons? Perhaps even at ADONE energies the hadronic final states contain some surprises.

d. Optimistic spectroscopy. Perhaps we can use $e^+e^- \to$ hadrons to see certain missing quark-model states. Some possibilities are mentioned by (Rosner, 1973b). As in purely hadronic reactions, kaons and η's may lead to low-background channels for resonance studies. Sensitivity to such particles is thus a desirable feature here.

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* First proposed by (Han, 1965; Nambu, 1965), and more recently discussed by (Greenberg, 1969 , Lipkin, 1973b), and others.

3. Two-photon resonance channels: $e^{\pm}e^{-} \rightarrow e^{\pm}e^{-}$ + hadrons

The process of Fig. 44 (reviewed by Brodsky, 1971 ; Walsh, 1973)* is dominated by small-angle lepton scattering and nearly real photons. To a good approximation, it thus leads to a hadron system moving along the ±z direction. Even without detecting the scattered leptons, one can select for such processes by tight cuts on transverse momentum balance (Kneis, 1973b). The background from e^+e^- annihilations will not be present when both stored lepton beams are e^-, as will be possible at DESY in a few years. Cross sections are expected to grow logarithmically with energy. The two-photon process thus will be entirely accessible to study. What does it tell us?

a. In $\gamma\gamma \rightarrow \pi^+\pi^-$ the low-energy regime is expected (Carlson, 1972a; Goble, 1972) to be dominated by a peak, due to ϵ (700) but shifted to much lower energies as a result of the absence of a PCAC zero. This zero is required below threshold in elastic $\pi\pi$ scattering but not in the inelastic case.

The process $\gamma\gamma \rightarrow f_0 \rightarrow \pi^+\pi^-$ is interesting as a test of various broken-SU(6) schemes referred to in section VI. The naive use of vector dominance for both photons, together with the "ℓ-broken" approach to describe $f_0 \rightarrow \pi\pi$ or $f_0 \rightarrow \omega\omega$, relates (Rosner, 1973b) the CM distribution in $\gamma\gamma \rightarrow f_0 \rightarrow \pi^+\pi^-$ to the helicity couplings in $B \rightarrow \omega\pi$:

$$W(\theta) \sim \sin^4\theta + \frac{1}{9}\left[\frac{F_0}{F_1}\right]^2_{B\rightarrow\omega\pi} (3\cos^2\theta - 1) \qquad (X.3)$$

Given the dominantly transverse nature of $B \rightarrow \omega\pi$ (see section II) this should lead to a dominantly $\sin^4\theta$ dipion distribution. Here, however, the effects of an S-wave state under the f_0 (see sections II, VIII) have not been taken into account, and other schemes for electromagnetic couplings (e.g., Gilman,

*See also (Terazawa, 1973).

1973d) may lead to different results (unknown at present).

b. $\underline{\gamma\gamma \to K\bar{K}}$. It may be possible to distinguish charged kaons from charged pions by time-of-flight if their momentum in the e^+e^- CM is not too large. This will be the case in $\gamma\gamma \to f' \to K^+K^-$. The distribution (X.3) will again be expected, with any differences from $\gamma\gamma \to f_0 \to \pi^+\pi^-$ ascribable to different S-waves under the two peaks.

c. $\underline{\gamma\gamma \to \pi^+\pi^-\eta \;(\eta \to \gamma\gamma)}$. The coupling of the η' to $\gamma\gamma$ is needed to resolve the question of octet-singlet mixing and possible non-octet parts of the electromagnetic current (see, e.g., Harari, 1968; Okubo, 1969; and section III. C.4). It may prove possible to detect the η' via the mode shown (Kneis, 1973b). The production of E(1420) and its decay into $\pi\pi\eta$ or $K\bar{K}\pi$ would provide conclusive evidence that its J^P is the favored value, 0^-. (A particle with $J^P = 1^+$, the other possible value, could not be formed in a $\gamma\gamma$ collision.)

d. Total $\gamma\gamma$ cross sections. These have been estimated by (Schrempp, 1971); by (Rosner, 1971d); and by (Gatto, 1973):

$$\sigma_T(\gamma\gamma) \simeq 0.24 + 0.27/s^{\frac{1}{2}}\ \mu b \quad (s \text{ in GeV}^2) \tag{X.4}$$

The energy-dependent part is due to the usual non-Pomeron trajectories f_0 and A_2. If duality holds, this part is an estimate of the total resonance contribution to forward elastic $\gamma\gamma$ scattering.

e. Control over masses ; opposite C. In contrast to $e^+e^- \to h^+h^-$, the two-photon process allows one to obtain a mass spectrum for decays of resonances into hadron pairs without varying beam energy. One should also mention the obvious facts that $\gamma\gamma \to$ hadrons checks for resonances with C = + and all possible J^P (except J = 1).

Other aspects of the $\gamma\gamma$ process (and the whole situation regarding resonance production in lepton storage rings) are reviewed by (Walsh, 1973). While "statistical" aspects (value of R, p^T distributions, etc.) are of great interest to most physicists studying hadron production by e^+e^-, the more conventional techniques of resonance physics are also useful here, and should not be neglected.

B. <u>One-Pion-Exchange (OPE)</u>

The dynamics of the $\pi\pi$ system has recently been clarified up to about 1.2 GeV in a series of experiments based on one-pion-exchange in $\pi^+p \rightarrow \pi^+\pi^-\Delta^{++}$ and $\pi^-p \rightarrow \pi^+\pi^-n$ (sections II, VIII). The advent of multi-particle spectrometers means that a number of similar processes will be accessible. One can comment very briefly on the various questions that may be posed in such cases.

1. <u>Pion-pion scattering</u>.

Inelastic channels are still not well studied, so that a reliable estimate of $\sigma_{tot}(\pi\pi)$ is not possible at present. It would be very interesting to have an estimate both of $\sigma_{tot}(\pi^-\pi^+)$ and $\sigma_{tot}(\pi^+\pi^+)$ *. The difference, averaged over resonances in the $\pi^-\pi^+$ system, would provide an estimate of the effects of ρ trajectory exchange. Theoretical ideas (based on SU(3) and factorizability) already exist for such effects.

The recurrence of the f_0 should be visible in an experiment of sufficient statistics. Higher-mass states are generally expected to be easier to study at higher energies, both because t_{min} is closer to zero and because the background due to nonresonant events such as N* production moves out to

*In this context see (Robertson, 1973).

larger average mass as energy increases. The disadvantage of going to higher energies is that one-pion exchange should decrease in energy with respect to natural-parity exchange. At present energies a balance holds between OPE ($|t| \ll 0.2\ \mathrm{GeV}^2$) and natural-parity exchange ($|t| \gg 0.2\ \mathrm{GeV}^2$) dominance (Estabrooks, 1973).

The parameters of the proposed S-wave state under the f_0 are still not well understood (sections II, VIII). In particular, what is its coupling to kaons, if any ? Such information is needed to complete our understanding of the 0^+ system of mesons, particularly to test mixing proposals such as that of section VIII.

Recent claims for a $\rho'(1600\text{-}1700\ ,\ 1^-)$ coupling to $\pi\pi$ with $X_{el} \sim 0.25$ (section II.A.3) must be tested. It would be a confirmation of the naive quark model ideas of section V to demonstrate the existence of two different ρ' ($\sim$ 1600-1700 , 1^-) states. In certain relativistic schemes, even a third is possible (Böhm, 1972).

2. Kaon-pion scattering

Some evidence has existed for a number of years for a broad S-wave $K\pi$ resonance somewhere above 1100 MeV (section II.A.5). Its pole parameters are as elusive as those of the $\epsilon(700)$. Its $K\pi$ width is very important in setting the scale of S-wave decays of the positive-parity mesons (section VI. C), and deserves further study. One would be satisfied with an estimate of the S-wave contribution to forward $K\pi$ scattering in the $K\pi$ Adler-Weisberger relation.

As in the case of $\pi\pi$ scattering, $\sigma_{tot}(K\pi)$ is (a) interesting and (b) not known. Interesting inelastic channels include $K\eta$, $K + (m\pi,\ m > 1)$, $KK\bar{K}$.

The $K_N(\sim 1760\ ,\ 3^-)$ (as well as any 1^- daughter) can be better understood in a clean $K\pi$ scattering experiment. Present data do not allow the separation of OPE up to such a high mass.

In $K^+ n \rightarrow K^+ \pi^- p$ at high energy, there is a sharp depletion of events between K(1420) and K(1760) (see, e.g., Firestone, 1971). This is reminiscent of similar behavior in $\pi\pi$ scattering just below $K\bar{K}$ threshold. Here, however, the corresponding threshold is not known, and the effect could be an Odorico zero (section VII) instead, at $\alpha_{K*}(2) = 5/2$. The situation deserves an analysis like that of (Protopopescu, 1973) once sufficient elastic and inelastic data become available.

3. Hyperon-pion scattering

At NAL and CERN II, the expected flux of Σ^- may approach that of present-day pion beams. At high energies these particles live long enough to allow their beams to be manipulated with relative ease. The diffractive process

$$\Sigma^- + \text{Nucleus} \rightarrow \Lambda + \pi^- + \text{Nucleus} \tag{X.5}$$

has already been observed (Hungerbuehler, 1973) (with no apparent resonances in the $\Lambda\pi^-$ system, however). The mere observation of (X.5) should allow an estimate of $g_{\Sigma\Lambda\pi}$. The processes

$$\Sigma^- + p \rightarrow \Sigma^- + \pi^+ + n \tag{X.6}$$

$$\rightarrow \Sigma^+ + \pi^- + n \tag{X.7}$$

$$\rightarrow \Lambda + \pi^0 + n \tag{X.8}$$

$$\rightarrow \Lambda + \pi^+ + \pi^- + n \tag{X.9}$$

$$\rightarrow \Sigma^- + \pi^- + \Delta^{++} \qquad \text{(X.1(}$$

all involve OPE contributions, which conceivably can be isolated. They are interesting for various reasons.

a. $\Sigma^-\pi^+ \to \Sigma^\mp\pi^\pm$. The known Λ and Σ resonances are almost always found via their couplings to $\bar{K}N$. Exceptions (in production experiments) are not susceptible to clear-cut phase shift analyses. A number of hyperon resonances in the quark model are expected to couple very weakly to $\bar{K}N$, however. These can be seen in Table D. I. There are more concrete indications, however, of substantial couplings to $\Sigma\pi$ of a number of states - some of which have not been observed in $\bar{K}N$ channels. The Adler-Weisberger relation for $\pi\Sigma$ scattering is very poorly saturated by the known hyperons (Babu, 1967; Gilman, 1968a). This is understandable if a few states are present which decouple from $\bar{K}N$ but not from $\pi\Sigma$. For example, the study of the $1/2^-$ Λ states indicates (Petersen, 1972; Faiman, 1972) the need in the quark model for three $\Lambda(1/2^-)$ resonances:

- $\Lambda(1405)$, coupling to $\Sigma\pi$ and $\bar{K}N$ (below threshold) , (X. 11)
- $\Lambda(1670)$, coupling largely to $\Lambda\eta$, (X. 12)
- Λ(unseen), coupling largely to $\Sigma\pi$ ($\Gamma_{\Sigma\pi} \simeq 400$ MeV !) (X. 13)

The last could be observed only in $\Sigma\pi$ scattering. Other resonances expected to contribute strongly to $\Sigma\pi$ scattering are:

- $\Sigma(1385\ ,\ 3/2^+)$
- $\Lambda(1520\ ,\ 3/2^-)$
- $\Sigma(\sim 1600\ ,\ 1/2^+)$ (needs confirmation)
- $\Sigma(1670\ ,\ 3/2^-)$ (X. 14)

- $\Lambda(1690\ ,\ 3/2^-)$
- $\Lambda(1815\ ,\ 5/2^+)$
- $\Lambda(1830\ ,\ 5/2^-)$

as well as an unknown set of $\Sigma\,(1/2^-)$ states, one or two Σ (unseen in $\bar{K}N$, $3/2^-$) and a broad Λ (unseen in $\bar{K}N$, $3/2^-$). (see Eqs. (V.17), (V.18) for predictions for the unseen Λ's by Faiman, 1972).

b. $\underline{\Sigma\pi \to \Lambda\pi}$. This should be an excellent place to see a $\underline{56}$ (8,2) $\Sigma(1/2^+)$ (Roper partner, perhaps the $\Sigma(1580)$ mentioned in section IX.D.2c), to sort out the S-wave states $\Sigma(1/2^-)$ mentioned earlier, and to clarify the properties of $\Sigma\,(1670\ ,\ 3/2^-)$ and other states of the same J^P.

c. $\underline{\Sigma\pi \to \Lambda\pi\pi}$. This channel can be used to study resonances decaying into $\Sigma(1385)\pi$, notably $\Lambda(1520\ ,\ 3/2^-)$ and $\Lambda(1690\ ,\ 3/2^-)$. Some question exists as to the $\Sigma(1385)\pi$ branching ratio of the latter (cf. Prevost, 1973 and Faiman, 1972).

d. $\underline{I = 2\ \Sigma\pi\text{ channel}}$. The reaction (X.10) can be used to study $\Sigma^-\pi^- \to \Sigma^-\pi^-$. This process is interesting as an exotic channel and from the standpoint of Regge models (which should apply at fairly low energies if the cross section has no bumps as a function of $m_{\Sigma\pi}$).

An experiment to study the interactions of Σ^- in hydrogen is underway at Brookhaven (Engler, 1973). Many of the above considerations hold as well for Λ beams, of course, e.g. in $\Lambda p \to \Lambda\pi^-\Delta^{++}$.

(Lipkin, 1973e) has suggested the use of hyperon beams to study diffractive excitation of resonances that could not be produced by single-particle exchange, such as members of the $\underline{20}$ of SU(6). The data of (Hungerbuehler, 1973) for reaction (X.5) show no such diffractively produced effect up to 1.6 GeV, but it is quite possible that the first 20 lies higher in mass (see Fig. 29). Other suggestions include the Coulomb excitation of hyperons and the measurement of hyperon-nucleon total cross sections (whose importance was mentioned in section VII).

C. Track-Sensitive Targets and Other Means for Detecting Neutrals

A track-sensitive target (TST) involves surrounding a hydrogen target with a material with high γ-ray conversion efficiency to detect multiple neutral particles. A recent experiment at the Rutherford Laboratory has studied the interactions of 4 GeV/c π^+ in such a system. Some questions relevant to that experiment are a sample of what can be learned (I am grateful to G. Gidal for a conversation leading to this list), and are shown in Table XXVII. Only meson resonances are listed, since baryons are better studied elsewhere in general.

A different approach is to take the questions of relevance to SU(3) and SU(6) meson multiplets, and see if they can be answered by more information about neutrals. These are listed in Table XXVIII (some were discussed in section V). In many cases the questions are ones best addressed using large statistics and detailed partial-wave analyses rather than final states involving neutrals. The following subsection (D) discusses questions of this type. Those tests involving more than one neutral particle generally do so because at least one η, ω, or other I = 0 particle is contained in the final state. (An exception is the case of three π^0's, which can only be in an I = 1 state. By comparing $\pi^+ p \rightarrow (3\pi^0)\Delta^{++}$ and $\pi^+ p \rightarrow (\pi^+\pi^-\pi^0)\Delta^{++}$, one can begin to separate out the isospins of the neutral three-pion system, including performing a subtraction to estimate pure I = 0 production.)

Many interesting decays involve η's or ω's combined with other neutrals. It may be of interest to produce certain $\eta\pi$ or $\omega\pi$ resonances [notably $\delta(1970)$, A_2 or B(1235)] via charge exchange on protons, leading to the need to detect $\eta\pi^o$ or $\omega\pi^o$ final states. One wishes to do this, for example, to study production mechanisms. Nothing is known about $\eta\eta$ resonances, which could test for the proposed S-wave effect under the f_0. The study of $A_2^\pm \rightarrow B^\pm\pi^o$ requires the observation of an $\omega\pi^\pm\pi^o$ final state. This decay is a valuable source of information on matrix elements of the axial charge Q_5 between states of the L = 1 quark model multiplet (see section VI). (It is less convenient to study $A_2^o \rightarrow B^\pm\pi^\mp$ because of production and background difficulties.)

Even if a resonance were able to decay into pions, a channel involving at least one η could provide lower background. For example, the A_2 is a very clear peak in $\eta\pi^-$ (Key, 1973), and the $\delta(970)$ has been seen in $\pi^-p \rightarrow \eta\pi^-p \rightarrow \gamma\gamma\pi^-p$ as well (Conforto, 1973; section II. A.5). The suggestion in Table XXVIII of an I = 1, $J^{PC} = 2^{--}$ $A_2\pi$ resonance (m = 1.6 to 1.8 GeV) could be tested in

$$\begin{array}{l} \pi^- + p \longrightarrow A_2 + \pi^o + p \\ \qquad\qquad\quad \lfloor\!\rightarrow \eta\pi^- \\ \qquad\qquad\qquad \lfloor\!\rightarrow \gamma\gamma \end{array} \tag{X.15}$$

if neutrals could be detected. This might be a cleaner channel than $\pi^-p \rightarrow \pi^-\pi^-\pi^+\pi^o p$.

D. Multi-particle spectrometers

The study of $\pi N \rightarrow (3\pi)N$ in large-scale compilations of bubble-chamber data (section II. A.4) has paved the way for further such analyses of multi-particle mesonic states. In order to gather sufficient data on such states, one must resort to counter experiments with geometrical acceptance comparable to that of bubble chambers.

The diffractive production of the three-pion system already is under study at OMEGA at CERN (Armenise, 1970). One of the crucial questions here is whether a "real" A_1 and A_3 are hiding under the Deck-type $\rho\pi$ ($J^P = 1^+$) and $f_0\pi$ ($J^P = 2^-$) peaks at ~ 1100 and ~ 1600 MeV respectively.

The non-diffractive channel now being studied at OMEGA (Dowell, 1970)

$$\pi^- p \rightarrow \pi^+\pi^-\pi^o n \qquad \text{(X.16)}$$

is extremely important to search for the isoscalar partner of the B (possibly $\Gamma \gtrsim 400$ MeV into $\rho\pi$!) and for the neutral A_1. The unfolding of these two states from one another depends on a detailed Dalitz plot analysis and should not be trivial. Some other production configurations for studying various of the L = 1 $q\bar{q}$ mesons as well as higher-mass states are discussed by (Fox, 1973). This work is a careful estimate of expected cross sections. It is an essential reference for anyone hoping to clear up what Fox and Hey call the "Great Meson Scandal". (The L = 1, J $\leq$ 1 mesons are much too poorly determined experimentally, especially when we compare them with what we know about L = 1 baryons.)

The mesons that would be classified as $q\bar{q}$, L = 2 (mass above 1600 MeV) are of great theoretical interest because of their varied decay modes. Some of these are shown in Table XXVIII. The higher symmetries mentioned in section VI lead to predictions such as (Hey, 1973b)

$$\frac{\Gamma_{\ell=0}\left[\rho(2^{--}) \rightarrow A_2\pi\right]}{\Gamma_{\ell=0}\left[A_3(2^{-+}) \rightarrow f_0\pi\right]} = 4/3 \qquad \text{(X.17)}$$

modulo any necessary kinematic corrections (which should be small). These two processes involve decays of an L = 2 state to an L = 1 state and a pion. Many predictions can be made for L = 2 $\rightarrow$ L = 0 + (pion), such as relations among $g \rightarrow \omega\pi$ $g \rightarrow \pi\pi$, $\rho(2^{--}) \rightarrow \omega\pi$, and $A_3 \rightarrow (\rho\pi)$ (see Hey, 1973b, and Table XVII). One way of testing for the decay $\rho(2^{--}) \rightarrow A_2\pi$ referred to above, of use in a multi-particle spectrometer, would be via the decay $\rho^{\pm}(2^{--}) \rightarrow A_2^{\pm}\pi^{o} \rightarrow K^{\pm} K_S^{o} \pi^{o}$. In general processes with strange particles can be selected using triggers based on V^{o} events, so that their low statistics pose no problem.

Baryon-exchange processes are ideal for study in multi-particle spectrometers. One can look for elusive states like the A_1, performing a partial-wave analysis of the three-pion system in $\pi^{\pm}p \rightarrow p_{fast}(\pi^{\pm}\pi^{+}\pi^{-})$. One can look for exotic mesons (section VII) in such processes as $\pi^{+}p \rightarrow \Lambda + X^{++}$, with fast forward Λ. One can study Ξ^{*} production in $K^{-}p \rightarrow K^{+} + (\Xi^{*-})$, triggering either on K^{+} or on high multiplicities associated with Ξ^{*} decays. All of these suggestions have been proposed and are at various stages of implementation at CERN or Brookhaven. A further experiment, ideally suited to this case, would involve placing a strong limit on couplings to nucleons of states like ϕ and f' in $\pi^{-}p \rightarrow n_{fast} K^{+}K^{-}$. Many dual schemes and quark models forbid this coupling (see section VII), but it has never been studied satisfactorily.

E. Coulomb Dissociation of Hadrons

The experimental aspects of this interesting field have been mentioned by (Dar, 1971).*Examples are

$$\pi^{-} + Z \rightarrow \rho^{-} + Z \tag{X.18a}$$

$$n + Z \rightarrow \Delta^{o} \text{ or } N(1470)^{o} + Z \tag{X.18b}$$

$$K^{-} + Z \rightarrow K^{*-} + Z \quad , \tag{X.18c}$$

*See also the recent results of (Edelstein, 1973).

each of which gives new information not directly available. (The baryonic reaction allows the study of $\gamma n \rightarrow$ (resonances) in a manner independent of deuteron effects.)

An example of a prediction that can be checked using (X. 18a) is Eq. (III. 15). Coulomb dissociation of hyperons also has been suggested (Lipkin, 1973e; section X. B.3).

F. Fundamentally High-Energy Processes

A number of resonance studies may depend crucially on high energies. Some of these have been discussed in detail by (Rosner, 1971d). They include diffraction production of high-mass states, decays involving rare (heavier) final states, colliding-beam studies using the two-photon process (see subsection A, above), the study of resonances in the "pionization" region (if any), correlations in final lepton pairs, excitation of constituents, and "charmed" particles (Snow, 1973).

1. Diffractive production of high-mass states

Very high energies allow the testing of various selection rules for diffractive production. The diffractive excitation of baryon resonances is already under study in a triggered bubble chamber experiment at SLAC (J. Ballam, private communication).* One can imagine similar experiments at still higher energies, such as

$$\pi^{\pm} + p \rightarrow \pi^{\pm}(\text{fast}) + \underbrace{(p\pi^{+}\pi^{-})}_{N^{*}}(\text{slow}) \quad , \tag{X.19}$$

in which the slow particles are detected in a bubble chamber and analyzed according to the method of (Ascoli, 1973). The decays

$$N^{*} \rightarrow \Delta\pi \tag{X.20}$$

*See (Barish, 1969).

have a double significance in such an approach. Given independent information about their helicity structure from studies such as those described in section VI, one can obtain the helicities and J^P of the produced N*'s, thus learning about diffraction. Present data (Cashmore, 1973a, b) suggest that $\lambda = 3/2$ dominates in $N^*(1520\ ,\ 3/2^-) \rightarrow \Delta\pi$, and $\lambda = 1/2$ dominates in $N^*(1690\ ,\ 5/2^+) \rightarrow \Delta\pi$. The $N\rho$ system must probably also be taken into account in diffractive $N\pi\pi$ production.

Precise tests of factorization, in which (X. 19) is compared with $pp \rightarrow pN^*$, $pp \rightarrow pp$, and $\pi p \rightarrow \pi p$ (Freund, 1968b) are also of interest, since it is strongly suspected that the J-plane structure of the Pomeron is very complicated. Here partial-wave analyses would be very useful in identifying <u>specific</u> diffractively produced states.

It has recently been suggested that the rise in total hadron-hadron cross sections (Gorin, 1971; Amaldi, 1973)* at Serpukhov and ISR energies may be due directly to increased diffractive production of high-mass states (Capella, 1973). Certainly there is a correlation between the two effects in proton-proton interactions, and it would be interesting to check this suggestion as well for K^+p (the other case in which a rising σ_T has already been seen). The precise nature of such states also needs much clarification: how does the multiplicity associated with their decays grow with mass, for example ?

2. <u>Decays involving rare (heavier) final states</u>

Whereas pionic correlations at high energies tend to obscure resonant

*See also (Amendolia, 1973).

behavior simply because so many pions are produced, the same may not be true for $K\bar{K}$ or $B\bar{B}$ pairs. One has in mind here a sort of multiperipheral picture, in which propagation of strangeness or baryon number over large distances in rapidity down the multiperipheral chain could be suppressed. The production of <u>known</u> resonances could then be studied, say, via their $K_S^o K_S^o$, $K^\pm K_S^o$, or K^+K^- decay models, and new resonances could perhaps emerge. One could also look for $\Lambda\bar{\Lambda}$ pairs. Such "survey" experiments would be ideal at the ISR.

3. Two-photon processes

The advantage of high energies here is that the cross section for production of a given-mass final hadronic state via Fig. 44 grows logarithmically with energy. A calculation (Rosner, 1971d) obtains the following cross sections for σ(ee $\rightarrow$ ee + hadron), based on (X.4):

Range of $\sqrt{s}$, GeV	E_{CM} = 6 GeV	E_{CM} = 30 GeV	
.3 to 1	11×10^{-33} cm^2	30×10^{-33} cm^2	
1 to 2	1.7×10^{-33} cm^2	6.9×10^{-33} cm^2	(X.20)
2 to 6	0.6×10^{-33} cm^2	5.1×10^{-33} cm^2	
6 to 30	–	1.8×10^{-33} cm^2	

The interesting region of 2 to 6 GeV in $\sqrt{s}$ (the energy in the hadronic CM) is much more accessible at total ee CM energy E = 30 GeV.

4. "Resonances" in the "pionization" region

Hadronic matter in collision has been compared to a gas or liquid (see, e.g., Wilson, 1970). This implies a statistical view of multiparticle production in which correlations play a relatively minor role. Deviations from this statistical pattern may show up when mass spectra are studied. For example, in 25 GeV/c $\pi^- p$ interactions, a handful of events are associated with a "puff" of pions with low CM energy, whose effects are visible in mass histograms of six-pion combinations (Erwin, 1970). Such phenomena may be associated with a more ordered phase of hadronic matter.

It has also been suggested that the overlap of resonances plays a crucial role in the determination of the density in rapidity space of particles emitted in a multi-hadron process (Nussinov, 1973). This would imply a more ordered structure than is usually assumed, so that the study of multi-particle correlations might prove quite fruitful.

5. Correlations in final lepton pairs

Experiments of the type (Christenson, 1970, 1973)

$$p + (\text{Matter}) \rightarrow \mu^+ + \mu^- + \ldots \tag{X.21}$$

are obvious sources of information regarding heavy vector bosons. None has been seen so far. In recent models of unified weak and electromagnetic interactions (Abers, 1973) a popular class of theories involves a neutral vector boson Z with mass

$$m_Z \geq 76 \text{ GeV} \tag{X.22}$$

whose detection is beyond the capability of existing accelerators.

6. Total cross section behavior: Excitation of constituents ?

The rise in total hadron-hadron cross sections is reminiscent of a similar behavior in $\sigma_T(n\,C^{12})$ at an energy in which N^* resonances can be excited in the carbon nucleus. Lower-energy parallels do exist in the two cases (Table XXIX). Perhaps the latest rise in $\sigma_T(K^+p)$ and $\sigma_T(pp)$ similarly means that the quarks in these hadrons are being excited to high-mass resonant states, or that quarks in different hadrons resonate with one another above a certain threshold. Let us imagine a case in which only qq systems resonated, for example. Then $\sigma_T(\bar{p}p)$ might not show the rise present in $\sigma_T(K^+p)$ and $\sigma_T(pp)$, and $\sigma_T(\bar{p}p) - \sigma_T(pp)$ would no longer show a smooth decrease as $\sim s^{-1/2}$. In general any large mass scale might be expected to show up as an anomaly in the usual Regge pole description. So far the data are consistent with unusual behavior of the Pomeron contribution alone, which is explained in at least one model (Capella, 1973) without reference to an intrinsically large mass scale.

7. "Charm" (see Snow, 1973)

The term "charmed particle" has several different meanings. A "three-triplet" particle in which the triplet index (e.g., "color") is not coupled to an overall SU(3) singlet is sometimes spoken of as charmed. Another (earlier) meaning of the term describes the degree of freedom provided by a fourth quark (u'), an SU(3) singlet with charm C = +1 (the others have C = 0), I = 0, and charge +2/3. We shall refer to this as "SU(4) charm". The inclusion of this quark allows for a straightforward analogy between leptonic and hadronic weak currents, and in particular permits the suppression of neutral strangeness-changing currents (which would be analogous to $\mu \longleftrightarrow e$ and $\nu_\mu \longleftrightarrow \nu_e$ transitions in the leptonic case) (see Glashow, 1970; Weinberg, 1972).

In either case one is confronted with a new quantum number. "Color" charm may be conserved at an unknown level. The mass threshold for production of charmed particles is also unknown. In $e^+e^- \rightarrow$ hadrons (subsection A, above) one interpretation of the rise in R between $E_{CM} = 3$ and $E_{CM} = 5$ GeV is that the threshold for $\gamma \rightarrow$ "color" charm has been passed. In theories with a fourth quark, u', this quark cannot be too massive, or the effects of suppression of neutral $\Delta S \neq 0$ currents are lost. An estimate (Lee, 1973) based on $K_L^o \rightarrow \mu^+\mu^-$ gives upper limits of around 7 GeV, depending on the class of theory.

One of the simplest ways to produced an SU(4) charmed hadron would be in a neutrino reaction:

$$\nu + n \rightarrow \mu^- + (h_{charmed})^+ \qquad (X.23)$$

In the conventional picture (Weinberg, 1972) the amplitude for this process would be suppressed by a factor $\sim \sin\theta$ (θ = Cabibbo angle) relative to the elastic case $\nu n \rightarrow \mu^- p$, and phase space would of course lead to further suppression. The detection of $h_{charmed}$ would then depend on whether it was an isolated level or had many nearby charmed levels. In the first case, the lepton energy loss would show a peak at the mass of the charmed state, while in the second a threshold effect would occur. One could either use a monochromatic neutrino beam and study the energy of the final muon (missing-mass spectrometer) or study the final hadron state calorimetrically (effective-mass spectrometer).

G. Summary, High-Energy Experiments

The major feature of high-energy hadronic interactions will be the large number of variables associated with the produced final states. Resonance production tends to be obscured in such cases as a result of huge combinatorial backgrounds. The suggestions presented here are just a few ways of continuing to learn about resonances under such circumstances. We have seen that in many cases high energies are a help rather than a hindrance, whether for technical reasons or because of new resonant effects that may be uncovered only at the highest energies.

XI. CONCLUSIONS

In the past decade, the spectroscopic study of elementary particle resonances has led to the confirmation of SU(3), the partial understanding of higher symmetries like $SU(6)_W$ and the still-controversial idea of duality. By far, the greatest puzzle associated with these successes remains the fact that they can be visualized in terms of fundamental constituents (quarks) which have not yet been observed. This very non-observance of quarks makes the continued study of resonances a search for fundamental laws rather than a mere working out of consequences of known laws. In this respect hadronic and nuclear spectroscopy are very different from one another.

The basic questions being addressed in hadron spectroscopy are similar to those being studied elsewhere, e.g., in deep inelastic leptoproduction in the study of nonresonant effects in $e^+e^- \rightarrow$ hadrons, and in proton-proton collisions at high energies. These questions include the charge, spin, and statistics of fundamental constituents; the forces binding the constituents to one another; the laws governing pair production of constituents (as in Figs. 30a and 43); and so on. The spectroscopic approach probes low-energy properties (long-range behavior) while the others are concerned with short-distance behavior. There is great insight obtained in trying to relate the two descriptions to one another, as we have seen in section VI. The "short-distance" descriptions cannot describe how quarks recombine into hadrons, or how they arrange to disguise themselves so effectively. Theories which do answer such questions are likely to have much to say about the spectroscopic laws we have described.

The quark model for classifying resonances is now compelling enough that we must subject it to serious experimental tests. There is evidence for mesonic ($q\bar{q}$) and baryonic (qqq) states with orbital excitations L=0, 1, 2, as well as fragmentary evidence for radial excitations. The observed resonances <u>all</u> fit into this pattern, a non-trivial success. On the other hand, it is necessary to continue the search for "exotics" (states which cannot be described by $q\bar{q}$ or qqq), and to fill the gaps in suggested multiplets. This work is continuing satisfactorily. Our picture of K^+N scattering (an exotic channel) is improving steadily, to the extent that we shall probably have to allow for a description of at least one exotic resonance shortly. Gaps in the existing nonexotic multiplets continue to be filled, mainly in the case of the baryons. New high-statistics experiments, new production and detection techniques, and partial-wave analyses are expected to lead to similar advances for the mesons.

In describing decays of resonances we have been aided both by naive and (more recently) by more abstract algebraic pictures. Much light has been shed on these models by experiments on "SU(3)-inelastic" reactions such as $\gamma N \rightarrow \pi N$ and $\pi N \rightarrow \pi \Delta$. We have learned that the collinear symmetry $SU(6)_W$ (ΔL_z=0) cannot be applied to decays of L-excited hadrons because a hadron with $L_z \neq 0$ has quarks moving transversely. The understanding of these effects from a more basic standpoint will be aided tremendously by more accurate and complete data in the channels just mentioned, in SU(3)- and SU(6)-related reactions, and in resonance leptoproduction.

Any observed breakdown of scaling behavior in $e^+e^- \rightarrow$ hadrons and $\ell + N \rightarrow \ell' +$ hadrons can be analyzed in usual resonance terms. At the very least, this approach may be expected to yield interesting threshold effects, if not discrete states. The host of new particles associated with spontaneously broken gauge symmetries of the weak and electromagnetic interactions might show up as resonances. So could the particles responsible for binding quarks to one another. The likely existence of a large mass scale in such theories could well be associated with a similar scale associated with spacing of energy levels, leading to a whole new level of hadron spectroscopy. Perhaps such findings would help in our understanding of resonances in the 1 to 2 GeV mass range, whose rich structure is ripe for a self-consistent dynamical theory.

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APPENDIX A

PARTIAL-WAVE DECOMPOSITION IN $1^+ \to 1^- 0^-$ DECAYS

By spin-parity conservation, the decay $1^+ \to 1^- 0^-$ contains final orbital angular momenta $\ell = 0, 2$. These are related to helicity amplitudes as follows. Consider the normalized helicity amplitudes F_λ, obeying

$$|F_0|^2 + 2|F_1|^2 = 1 \tag{A.1}$$

These may be decomposed in terms of normalized partial-wave amplitudes $a_{\ell=0}$, $a_{\ell=2}$:

$$F_\lambda = \sum_\ell \sqrt{(2\ell+1)/3}\ (1\lambda\ \ell 0 \mid 1\lambda)\, a_\ell \tag{A.2}$$

so that

$$\begin{aligned} F_0 &= a_0/\sqrt{3} - a_2\sqrt{2/3} \\ F_1 &= a_0/\sqrt{3} + a_2/\sqrt{6} \end{aligned} \tag{A.3}$$

Since $|a_0|^2 + |a_2|^2 = 1$, we have

$$\frac{\Gamma_{\ell=2}}{\Gamma_{\ell=0} + \Gamma_{\ell=2}} = |a_2|^2 = \frac{2}{3}\,|F_1 - F_0|^2 \tag{A.4}$$

Pure S-wave corresponds to $|F_0|^2 = |F_1|^2 = 1/3$ and $F_0 = +F_1$; pure D-wave corresponds to $F_0 = -2F_1$ and $|F_0|^2 = \frac{2}{3}$.

APPENDIX B

0^+ MIXING MODEL

We start with three "unmixed" states: an SU(3) singlet dilaton $|1\rangle$ whose mass m_1 is near that of the $\epsilon(700)$, and two quark model states

$$|2\rangle \equiv (u\bar{u} + d\bar{d})/\sqrt{2} \ , \qquad m_2 \simeq m_{S*} = 997 \text{ MeV} \tag{B.1}$$

$$|3\rangle \equiv s\bar{s} \ , \qquad m_3 \simeq m_{\epsilon'} = 1240 \text{ MeV} \ . \tag{B.2}$$

The transitions $1 \leftrightarrow 2$, $1 \leftrightarrow 3$ are assumed to be SU(3) invariant. The mass matrix $\mathcal{M}$ is then

$$\mathcal{M} = \begin{bmatrix} m_1^2 & x\sqrt{2} & x \\ x\sqrt{2} & m_2^2 & 0 \\ x & 0 & m_3^2 \end{bmatrix} \ , \tag{B.3}$$

where x is a small parameter. We shall also assume for the sake of definiteness that

$$m_2 = m_\delta = 970 \text{ MeV} \tag{B.4}$$

This is an assumption of the "ideal" nature of the 0^+ $^3P_0$ nonet before mixing with the dilaton occurs.

Together with the demand that the three eigenvalues of $\mathcal{M}$ be

$$\begin{aligned} \lambda_1 &= m^2 = m_1^2 + \delta_1 \\ \lambda_2 &= m_{S*}^2 = m_2^2 + \delta_2 \ , \\ \lambda_3 &= m_{\epsilon'}^2 = m_3^2 + \delta_3 \end{aligned} \tag{B.5}$$

equation (B.4) specifies the parameters of $\mathscr{M}$ uniquely. For the small parameters $\delta_i (i=1,2,3)$ we find

$$\begin{aligned} \delta_1 &= 0.013 \text{ GeV}^2 \\ \delta_2 &= 0.053 \text{ GeV}^2 \\ \delta_3 &= -0.066 \text{ GeV}^2 \end{aligned} \quad , \tag{B.6}$$

and

$$x = \pm .115 \text{ GeV}^2 \tag{B.7}$$

The mixing is thus roughly 10% in the mass matrix. Clearly this is very sensitive to the S*-δ mass difference and to the initial nonet ansatz, however.

The corresponding eigenvectors, in 1-2-3 space, are

$$\epsilon \cong \begin{bmatrix} 1 \\ \pm .32 \\ \pm .11 \end{bmatrix} \tag{B.8}$$

$$S^* \simeq \begin{bmatrix} \mp .32 \\ 1 \\ 0 \end{bmatrix} \tag{B.9}$$

$$\epsilon' \simeq \begin{bmatrix} \mp .11 \\ 0 \\ 1 \end{bmatrix} \quad , \tag{B.10}$$

where we have not bothered to normalize and continue to work to first order in small parameters.

The partial decay amplitudes of interest are then related to

$$< \pi | Q_5 | S^* > \simeq \mp .32 < \pi | Q_5 | 1 > + < \pi | Q_5 | 2 > \approx 0 \quad , \tag{B.11}$$

$$< \pi | Q_5 | \epsilon > \simeq < \pi | Q_5 | 1 > \tag{B.12}$$

and

$$< \eta | Q_5 | \delta > = < \pi | Q_5 | 2 > / \sqrt{3} \tag{B.13}$$

The last relation follows from SU(3). Setting the scale of $< \pi | Q_5 | 2 >$ by the value

$$\Gamma(\delta \to \eta \pi) = 60 \text{ MeV} \tag{B.14}$$

(see Table XV), demanding that (B.11) vanish to cancel out the $\pi\pi$ width of the S^*, and using PCAC to relate these matrix elements to observed partial widths, we obtain a prediction

$$\Gamma \left[\epsilon (700) \to \pi\pi \right] = 1900 \text{ MeV} \tag{B.15}$$

This is far too large to be compatible with the Adler-Weisberger relation for $\pi\pi$ scattering, let alone considerations of broken scale invariance: it correspor to

$$< \pi | Q_5 | 1 > \simeq 1.7 \tag{B.16}$$

The scale (B.14) must be about a factor of three smaller if (B.15) is to become something reasonable.*

*The $SU(6)_W$ relations between Eq. (B.14) and $\Gamma_{\ell=0}(B \to \omega\pi)$, however, will then have been strained beyond the breaking point. (See section VI.C, Table XVI.)

The predicted partial width for $\epsilon' \to \pi\pi$, based on Eq. (B.14), is

$$\Gamma\left[\epsilon'(1240) \to \pi\pi\right] \simeq 150 \text{ MeV} \quad . \tag{B.16}$$

This, too, could be scaled down by a factor of three without much difficulty, given present experimental uncertainty.

APPENDIX C

EXPRESSIONS FOR PARTIAL WIDTHS IN TERMS OF MATRIX ELEMENTS OF OPERATORS

Pion emission:

$$\Gamma(A \to B\pi^-) = \frac{1}{\left(4\pi f_\pi^2\right)} \frac{p_\pi}{2J_A+1} \frac{\left(m_A^2 - m_B^2\right)^2}{m_A^2} \sum_\lambda \left| \langle B,\lambda | \frac{Q_5^1 - iQ_5^2}{\sqrt{2}} | A,\lambda \rangle \right|^2 \tag{C.1}$$

Photon emission:

$$\Gamma(A \to B\pi^-) = \frac{e^2}{\pi} \frac{p_\gamma^3}{2J_A+1} \sum_\lambda \left| \langle B,\lambda | D_+^3 + \frac{1}{\sqrt{3}} D_+^8 | A,\lambda-1 \rangle \right|^2 \tag{C.2}$$

(From (Gilman, 1973d).) Here p and p_γ are final c.m. 3-momenta of the emitted pion or photon, and λ are the helicities of the final hadrons.

APPENDIX D

$SU(6) \times SU(3)$ FACTORS

In order to illustrate the predictions of SU(6) values of f/d for $8 \rightarrow 8 \times 8$ couplings, we have chosen to quote the factors $\sum_{i=f,d} C_{SU(6),i}\, C_{SU(3),i}$, where $C_{SU(6)}$ are the factors tabulated by (Cook, 1965) and $C_{SU(3)}$ are those tabulated by (Lasinski, 1973). The baryon-first conversion advocated by (Levi-Setti, 1969) is used. The results are shown in Table D. 1. For completeness, since such results are also predicted by $SU(6)_W$, we include decays $1 \rightarrow 8 \times 8$ and $10 \rightarrow 8 \times 8$. This allows one to relate decays of a given J^P $\underline{70}$, (8, 2) state to those of the $\underline{70}$, (1, 2) or $\underline{70}$, (10, 2) state with the same J^P.

Our format is similar to that of (Faiman, 1972), but the coefficients are different, since they involve $SU(6)_W$ factors. Within a given $SU(3) \times SU(2)$ multiplet, of course, the ratios are the same. We also prefer to square the coefficient, preserving its sign however.

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TABLE I

Comparison of old and new missing-mass spectrometer results; old and new $\bar{p}p$ resonances. For a more complete list of new data on high-mass bosons, see (Diebold, 1972; Smith, 1973).

Old MMS (Focacci, 1966)			New MMS (Bowen, 1973)		
Name	M	Γ	Name	M	Γ
R_1	1632 ± 15	≤ 21	{g, A_3}	1648 ± 7	139 ± 31
R_2	1700 ± 15	≤ 30			
R_3	1748 ± 15	≤ 38			
S	1929 ± 14	≤ 35	{Possible S}	1934 ± 13	133 ± 70
T	2195 ± 15	≤ 13	{None observed}		
U	2382 ± 24	≤ 30			

Old $\bar{p}p$ (σ_T: Abrams, 1970)		New $\bar{p}p$ (Alspector, 1973)	
M^a	Γ^a	M	Γ
2187 ± 3	56 ± 8	2193^{+1}_{-2}	98^{+8}_{-6}
2362 ± 2	17 ± 10	2359 ± 1	165^{+18}_{-8}
		(Carroll, 1973b)	
		~1930	$\lesssim$30 MeV

[a] As fitted by (Alspector, 1973).

TABLE II

Comparisons of some recent determinations of the $\Xi^*(1530)$ width.

	Experiment	Quoted Width, MeV	Resolution, MeV	Number of Ξ^{*0} events
1.	J. Badier et al., Nucl. Phys. B37, 429 (1972)	11.0 ± 2.0	$2\sigma = 4.6$	~ 100
2.	C. Baltay et al., Phys. Letters 42B, 129 (1972)	9.0 ± 0.7	4.6	~ 1262
3.	S. Borenstein et al., Phys. Rev. D 5, 1559 (1972)	8.4 ± 1.4	FWHM = 5.2	324
4.	L. Kirsch et al., Nucl. Phys. B40, 349 (1972)	11.0 ± 1.8	FWHM ≃ 5.0	286

SU(3) fit of (Samios, 1973):

$$\Gamma(\Xi^* \to \Xi\pi) = 11.6 \text{ MeV}$$

World averages (earlier references from Lasinski, 1973):

(Lasinski, 1973): 9.1 ± 0.5 [a]

(Samios, 1973): 9.1 ± 1.3 [b]

[a]Statistical average.

[b]Takes account of spread in quoted values.

TABLE III

Comparison of experimental $3/2^+ \to 1/2^+ 0^-$ widths with SU(3) (Samios, 1973). The fit is satisfactory given the quoted error for $\Gamma(\Xi^*)$ (see, however, Table II).

$$J^P = 3/2^+$$

$$\chi^2 = 7.8/3C ; \quad |A_{10}| = 146.8 \pm 2.4$$

Decay	Experimental Γ(MeV)	SU_3 Predicted Γ(MeV)
$\Delta(1236) \to N\pi$	116 ± 6	107.2
$\Sigma(1386) \to \Sigma\pi$	3.6 ± 1.2	5.1
$\Sigma(1386) \to \Lambda\pi$	32.4 ± 5.5	35.3
$\Xi(1530) \to \Xi\pi$	9.1 ± 1.3	11.6

TABLE IV

Values of f obtained in fits to $8 \to 8 \times 8$ baryon resonance decays. Our normalization is such that $G_{\pi NN} \sim f+d$, and $f+d = 1$. In terms of g_F and g_D (coefficients of SU(3) Clebsch-Gordan coefficients as listed by Lasinski, 1973), $f = \left[1 + (3/\sqrt{5})\, g_D/g_F\right]^{-1}$. The $SU(6)_W$ predictions also follow from weaker considerations, and are discussed in section VI.

J^P	(Barbaro-Galtieri, 1972) f [$f+d \equiv 1$]	χ^2/d.f.	(Samios, 1973) f [$f+d \equiv 1$]	χ^2/d.f.	f [$SU(6)_W$]
$1/2^+$	-	-	.3 to .4	-	.4
$1/2^-$	$-.2 \pm .1$	15 [a]	$-.28 \pm .06$	3.2/3 [b]	$-.5$ [c]
$3/2^-$	$.66 \pm .09$	9.1/4	$.72 \pm .03$	.02/1	.625 [d]
$5/2^+$	$.38 \pm .04$ [e]	6.5/4	$.54 \pm .01$ [e]	6.2/4	.4
$5/2^-$	$-.13 \pm .05$	1.9/4	$-.16 \pm .02$	5.1/4	$-.5$
$7/2^-$	-	-	$.83 \pm .02$	2.3/3	.625

[a] Constrained fit; see (Barbaro-Galtieri, 1972). The decay $N(1530) \to N\eta$ is fit very badly, $\chi^2 = 5$.

[b] Larger error assigned to $N(1530) \to N\eta$ than in a.

[c] Prediction for unmixed (8, 4) octet. This assumption may be unreliable; see (Faiman, 1972).

[d] Prediction for unmixed (8, 2) octet. Mixing effects here are indeed likely to be small; see (Faiman, 1972).

[e] Discrepancy discussed in text.

TABLE V

N* and Δ states above 2 GeV from recent πN elastic phase shift analyses.

Resonance	Analysis:	(Almehed, 1972)[a] m	Γ	x_{el}	(Ayed, 1972)[a] m	Γ	x_{el}	(Wagner, 1972a) m	Γ	x_{el}	Possible Significance
F_{17}	$N(7/2^+)$	2000	200	.15	2050	183	.06	2300	-	-	$\underline{70}$, L=2: duality, quark model
D_{13}	$N(3/2^-)$	2075	150	.30	-	-	-	-	-	-	Radial excitation of $N(1520, 3/2^-)$
D_{15}	$N(5/2^-)$	2100	150	.20	2050	170	.09	-	-	-	Regge recurrence (R.r.) of $N(1535, 1/2^-)$
F_{15}	$N(5/2^+)$	2175	150	.26	2000	56	.09	-	-	-	Possible $\underline{70}$, L=2 or R.r. of $N(1470, 1/2^+)$
S_{11}	$N(1/2^-)$	2100	200	.50	2195	280	.16	"very wobbly"			Radial excitation of $N(1535, 1/2^-)$
D_{35}	$\Delta(5/2^-)$	2200	600	.25	-	-	-	-	-	-	R.r. of $\Delta(1650, 1/2^-)$
G_{17}	$N(7/2^-)$	2225	150	.33	2150	322	.20	2200	150	.18	R.r. of $N(1520, 3/2^-)$
G_{19}	$N(9/2^-)$	-	-	-	2130	250	.08	2340	300	.10	R.r. of $N(1670, 5/2^-)$
H_{19}	$N(9/2^+)$	above range of analysis			2240	289	.17	2275	250	.20	R.r. of $N(1690, 5/2^+)$
$H_{3,11}$	$\Delta(11/2^+)$	above range of analysis			2390	292	.10	2450	360	.12	R.r. of $\Delta(1950, 7/2^+)$
G_{39}	$\Delta(9/2^-)$	-	-	-	-	-	-	2225	300	.11	$\underline{56}$, L=3: duality, quark model

[a]As quoted by (Lovelace, 1972).

TABLE VI

"Complete" baryon multiplets of SU(3)

J^P	SU(3) dimension	Y=1 States I=1/2	Y=1 States I=3/2	Y=0 States I=0	Y=0 States I=1	Y=-1 States	Y=-2 States
$1/2^+$	$\underline{8}$	N(938)	-	Λ(1115)	Σ(1190)	Ξ(1320)	-
$3/2^+$	$\underline{10}$	-	Δ(1236)	-	Σ(1385)	Ξ(1530)	Ω(1670)[b]
$3/2^-$	$\underline{8}$ + $\underline{1}$	N(1520)[a]	-	Λ(1518)[a], Λ(1690)[a]	Σ(1671)[a]	Ξ(1820)[a,b]	-
$5/2^-$	$\underline{8}$	N(1674)	-	Λ(1829)	Σ(1767)	Ξ(1930)[b]	-
$5/2^+$	$\underline{8}$	N(1687)	-	Λ(1817)	Σ(1927)	Ξ(2030)[b]	-

[a]Mixtures with still another octet (or $\underline{10}$ for Σ, Ξ) not excluded.
[b]J^P not yet confirmed.

TABLE VII

Nonstrange baryons belonging to incomplete SU(3) multiplets[a]

J^P	I, Y;SU(3) dimension	State	SU(3) partners implied[b] Λ	Σ	Ξ	Ω
$1/2^{+}$ [d]	(1/2, 1); $\underline{8}$	N(1470)				
		N(1780)	2(1)	3(1)	3(0)	1(0)
	(3/2, 1);$\underline{10}$	Δ(1910)				
$1/2^{-}$	(1/2, 1); $\underline{8}$	N(1535)				
		N(1700)	2(1)[c]	3(1-2)	3(0)	1(0)
	(3/2, 1);$\underline{10}$	Δ(1650)				
$3/2^{+}$ [d]	(1/2, 1); $\underline{8}$	N(1860)				
	(3/2, 1);$\underline{10}$	Δ(1690) ?	1(1 ?)	3(1 ?)	3(0)	2(0)
		Δ(1890) ?				
$3/2^{-}$ [d]	(1/2, 1); $\underline{8}$	N(1730)	1(0)	2(1)	2(0)	1(0)
	(3/2, 1);$\underline{10}$	Δ(1670)				
$5/2^{+}$ [d]	(3/2, 1);$\underline{10}$	Δ(1890)	0(0)	1(0)	1(0)	1(0)
$7/2^{+}$	(1/2, 1); $\underline{8}$	N(2000)	1(1 ?)	2(1)	2(0)	1(0)
	(3/2, 1);$\underline{10}$	Δ(1950)				
$7/2^{-}$	(1/2, 1); $\underline{8}$	N(2190)	1(0)[c]	1(1)	1(0)	0(0)

[a] States below 2 GeV.

[b] Numbers in parentheses are those probably observed so far.

[c] One SU(3) singlet also observed.

[d] In addition to those noted in Table VI.

TABLE VIII

"Complete" meson multiplets: nonets or octets and singlets of SU(3)

J^{PC}	I=1, Y=0 members	I=1/2, |Y| =1 members	I=0, Y=0 members	
0^{-+}	$\pi^{\pm}(140)$	$K^{+}(494)$	η (549) ;	η' (958)
	$\pi^{0}(135)$	$K^{0}(498)$		
1^{--}	ρ(770)	K*(892)	ω(784) ;	ϕ(1019)
2^{++}	A_2(1310)	K_N(1420)	f(1270) ;	f'(1514)

TABLE IX

Mesons belonging to incomplete nonets

J^{PC}	I=1, Y=0 members	I=1/2, Y =1 members	I=0, Y=0 members
0^{++}	δ(970)	$K\pi$ state ,	ϵ (700)
		1100 - 1400 MeV ?	S*(997)
		(Needs confirmation)	ϵ'(1240)
1^{++}	A_1(1070)	$K\pi\pi$ state(s)	D(1285) ; ?
		between	
		1240 and	
1^{+-}	B(1235)	1400 MeV	? , ?
3^{--}	g(1680)	$K\pi$ state ,	ω(1675) , ?
		1760 MeV	
0^{-+}	?	?	E(1420)
1^{--}	ρ'(1500)	?	? , ?
2^{--}(?)	F_1(1540) or	L(1770):	? , ?
	S-wave $A_2\pi$ state	mixing	
2^{-+}	A_3(1640)	possible	? , ?

TABLE X

Single recurrences of baryons and mesons.
Only "established" (Lasinski, 1973) states are used.

State, J^P	Recurrence	Slope $= 2/\Delta m^2$	Remarks
<u>Baryons</u>			
$N(1520),\ 3/2^-$	$N(2190),\ 7/2^-$	0.80	
$\Lambda(1520),\ 3/2^-$	$\Lambda(2100),\ 7/2^-$	0.95	
$\Sigma(1193),\ 1/2^+$	$\Sigma(1915),\ 5/2^+$	0.89	
$\Sigma(1385),\ 3/2^+$	$\Sigma(2030),\ 7/2^+$	0.90	
$\Xi(1318),\ 1/2^+$	$\Xi(2030),\ 5/2^+$?	0.83	$\Xi(2030)$ not fully established
<u>Mesons</u>			
$\pi(140),\ 0^-$	$A_3(1640),\ 2^-$	0.74	A_3 not conclusively resonant
$K(496),\ 0^-$	$L(1770),\ 2^-$	0.70	L may be a mixture of K recurrence and another state
$K^*(892),\ 1^-$	$K_N(1760),\ 3^-$	0.87	$K_N(1760)$ not fully established

TABLE XI

Evidence for various baryon rest symmetry multiplets below ~2 GeV

Mass Range, GeV^2	$SU(6)_q$, L^P	Possible Candidates
.8 - 2.8	$\underline{56}$, 0^+	Filled (Fig. 27)
2 - ≃3.5	$\underline{70}$, 1^-	Many (Fig. 27)
2.8 - $\gtrsim$4	$\underline{56}$, 2^+	Many (Fig. 27)
~ 4	$\underline{70}$, 2^+	N(~ 2000, $7/2^+$)[a,b];
		possible Λ(~2000 - 2100, $7/2^+$)[c]
		behavior of Δ(1890, $5/2^+$)[b]
2 - ?	$\underline{56}$, 0^+	N(1470, $1/2^+$) [d]
~3 -	$\underline{70}$, 0^+	N(1780, $1/2^+$)[e] [d]

[a]Almehed, 1972; Langbein, 1973 (solution I).

[b]Faiman, 1973a.

[c]Barbaro-Galtieri, 1970b.

[d]Mixing between these two and between the N($1/2^+$) level expected from $\underline{70}$, 2^+ is possible.

[e]Assignment suggested on basis of couplings. See (Faiman, 1968; Heusch, 1970).

TABLE XII

Evidence for various meson rest symmetry multiplets below ~1.8 GeV

Mass Range GeV^2	L	$SU(6)_q \times SU(6)_{\bar{q}}$	Possible Candidates (J^{PC})
0 - 1	0	$(6,\bar{6})$	0^{-+}, 1^{--}: filled (Fig. 28)
~.5 - 2.3	1	$(6,\bar{6})$	0^{++}, 1^{++}, 1^{+-}, 2^{++}: many (Fig. 28)
2.8 - ?	2	$(6,\bar{6})$	1^{--}, 2^{--}, 2^{-+}, 3^{--}: many (Fig. 28)
2 - ?	0	$(6,\bar{6})$	E(1420) <u>if</u> 0^- (if 1^+, it fits into L=1, above). Possibly ρ' in γ-induced reactions.

TABLE XIII

Predicted and observed states in (56 + 70), $L^P = (2^+ + 0^+)$ below ~2 GeV
(aside from lowest <u>56</u>, L=0, which is filled)

	N	Δ, Ω	Λ	Σ, Ξ
$1/2^+$	3(2)	2(1, 0)	4(1?)	5(1?, 0)
$3/2^+$	4(1)	3(2?, 0)	5(1?)	7(?, 0)
$5/2^+$	3(1 or 2 [a])	2(1 or 2 [b], 0)	4(1)	5(1, 1)
$7/2^+$	1(1)	1(1, 0)	1(1 [c])	2(1, 0)

[a] Possible second F_{15} resonance around 2 GeV. See (Almehed, 1972) and (Faiman, 1973a).
[b] See (Faiman, 1973a). Mixing effects may indicate more than one state.
[c] See (Barbaro-Galtieri, 1970b).

TABLE XIV

Evidence for $\underline{70}$, $L^P = 3^-$ and $\underline{56}$, $L^P = 4^+$ baryon multiplets

Representation	Candidate
$\underline{70}$, $L^P = 3^-$	$N(2190, 7/2^-)$
	$\Lambda(2100, 7/2^-)$
	$\Sigma(2200, 7/2^-)$
$\underline{56}$, $L^P = 4^+$	$N(2220, 9/2^+)$
	$\Delta(2420, 11/2^+)$
	$\Lambda(2350, 9/2^+)$

For references, see (Lasinski, 1973).

TABLE XV

Comparison of Q_5 and $\tilde{Q}_5 = V^{-1} Q_5 V$

in the Melosh approach to pionic decays.

Group	Q_5	Additional piece in $\tilde{Q}_5$
$SU(3) \times SU(3)$ [a]	$(8,1) - (1,8)$ $L_z = 0$	$(3,\bar{3}) - (\bar{3},3)$ $L_z = \pm 1$
$SU(6)_W$ [b]	$\underline{35}(8,3)$ $L_z = 0$	$\underline{35}(8,3)$ $L_z = \pm 1$

[a]Numbers in parentheses refer to dimension of the two SU(3) representations corresponding to $V \pm A$.

[b]Underlined numbers are $SU(6)_W$ representations; numbers in parentheses refer to SU(3) and $SU(2)_W$ dimensions, respectively.

TABLE XVI

Partial widths for $\underline{35}$, L=1 mesons

Process	Γ_{expt}, MeV	Γ_{pred}, MeV PCAC	Γ_{pred}, MeV $P_*^{2\ell+1}$	$\tilde{\Gamma}$ [a]
D waves				
$A_2(1310) \to \rho\pi$	72 ± 10 [b]	72 (input)	50 [c]	$3D^2/80$
$B(1235) \to (\omega\pi)_{\ell=2}$	≈ 8 [d]	24	14	$D^2/48$
$A_1(1100) \to (\rho\pi)_{\ell=2}$	?	≈ 8	≈ 2	$D^2/48$
$A_2(1310) \to \eta\pi$	15 ± 3 [b]	16 [e]	19 [e]	$D^2/240$ [e]
$A_2(1310) \to \eta'\pi$	$\lesssim 1$ [f]	5 [g]	1.3 [g]	$D^2/120$ [g]
$f(1270) \to \pi\pi$	130 ± 20 [b]	110	175 [c]	$3D^2/160$
$K(1420) \to K\pi$	63 ± 7.5 [h]	49	76	$3D^2/320$
$K(1420) \to K^*\pi$	30 ± 6 [h]	23	16	$9D^2/640$
$K(1420) \to K\eta$	< 2.6 [h]	--	2.5 [i]	$D^2/960$ [i]
S waves [j]				
$B(1235) \to \omega\pi$	130 ± 20 [d]	130 (input)		$S^2/96$
$A_1(1100) \to (\rho\pi)_{\ell=0}$	?	175	460	$S^2/24$
$\delta(970) \to \eta\pi$	60^{+50}_{-30} [k]	90 [e]	185 [e]	$S^2/96$ [e]
$K_N(1100) \to K\pi$	?	485	450	$3S^2/128$
Helicity structures				
$B(1235) \to \omega\pi$	$\lvert F_0\rvert^2_{expt} = 0.13 \pm 0.05$	.04	.08	$\frac{F_0}{F_1} = \frac{S+2D}{S-D}$
$A_1(1100) \to \rho\pi$	$\lvert F_0\rvert^2_{expt} \simeq 1/3$	.54	.40	$\frac{F_1}{F_0} = \frac{S+D/2}{S-D}$
Relation $2\left(\frac{F_1}{F_0}\right)_{A_1} = \left(\frac{F_0}{F_1}\right)_B + 1$:		Exact	Approximate	
(Colglazier, 1971a,b)				

[a] $\tilde{\Gamma}$ is the partial width before correction for kinematic factors.

[b] Based on averages of (Lasinski, 1973).

[c] Best fit to $A_2 \to \rho\pi$ and $f_0 \to \pi\pi$ used as input.

[d] (Rosner, 1973c).

[e] Based on octet assignment for η: $\eta = (u\bar{u} + d\bar{d} - 2s\bar{s})/\sqrt{6}$.

[f] Based on recent bound by (Eisenstein, 1973).

[g] Based on singlet assignment for η': $\eta' = (u\bar{u} + d\bar{d} + s\bar{s})/\sqrt{3}$. The η' belongs to the $\underline{35}$ of $SU(6)_W$; it is the helicity-zero vector meson singlet which belongs to $\underline{1}$ of $\overline{SU}(6)_W$. Hence Zweig's rule (relating couplings of these two multiplets) is not used in making $SU(6)_W$ predictions involving η'. All η, η' predictions assume, of course, that no higher multiplets of the rest symmetry are admixed.

[h] (Aguilar, 1971).

[i] These predictions are of interest in section VII. D. 1.

[j] Predictions for decays of 1^+ kaons (including D waves and helicity structures) may be found in (Colglazier, 1971a).

[k] (Conforto, 1973), assuming 100% $\eta\pi$ decay of δ. (Lasinski, 1973) quote $\Gamma_\delta = 50 \pm 30$ MeV.

TABLE XVII

Partial widths (F waves) for $\underline{35}$, L=2 mesons.

Process	Γ_{expt}, MeV	Γ_{pred}, MeV PCAC[a]	Γ_{pred}, MeV $p_*^{2\ell+1}$ [b]	$\tilde{\Gamma}$[c]
$g(1680) \rightarrow \pi\pi$	$\simeq 40$[d]	40 (input)		$F^2/140$
$g(1680) \rightarrow \omega\pi$	$\simeq 28$[e]	27	12	$F^2/105$
$\omega(1675) \rightarrow \rho\pi$	$\Gamma_{tot} \simeq 140$; $\rho\pi$ dominant[f]	75	36	$F^2/35$
$K_N(1760) \rightarrow K\pi$	$\simeq 40 \pm 20$[g]	27	18	$3F^2/560$
$K_N(1760) \rightarrow K^*\pi$	$\simeq 20 \pm 15$[g]	19	7	$F^2/140$

[a]Based on (Gilman, 1973e).

[b](Hey, 1973b).

[c]Partial width before kinematic factor correction.

[d]W. Blum, CERN seminar, February, 1973: analysis of CERN-Munich data on $\pi^- p \rightarrow \pi^+\pi^- n$ at 17.2 GeV/c. See also (Hyams, 1973).

[e](Graham, 1972): $g \rightarrow \pi\pi / g \rightarrow \omega\pi = 1.4 \pm 0.7$.

[f]From (Lasinski, 1973).

[g](Carmony, 1973): $K_N \rightarrow K^*\pi / K_N \rightarrow K\pi = 0.54 \pm 0.24$.

TABLE XVIII

Partial widths for 70, L=1 baryon decays.

Process	Γ_{expt}, MeV	Γ_{pred}, MeV PCAC[a]	$p_*^{2\ell+1}$ [b]	$\tilde{\Gamma}$ [c]
D waves				
$N(1670, 5/2^-) \to N\pi$	60 ± 15 [d]	21	34	$D^2/360$
$\to \Delta\pi$	84 ± 21 [e]	82	45	$7D^2/180$
$\Sigma(1765, 5/2^-) \to \Lambda\pi$	16 ± 5	17	21	$D^2/360$
$\to \Sigma\pi$	1.4 ± 0.6	8	8	$D^2/540$
$\to \Sigma^*\pi$	$\simeq 12$?	10	4	$7D^2/1080$
$\Lambda(1830, 5/2^-) \to \Sigma\pi$	22 ± 25	49	59	$D^2/120$
$\to \Sigma^*\pi$	?	67	40	$7D^2/240$
$\Delta(1670, 3/2^-) \to N\pi$	33 ± 15	19	30	$D^2/432$
$\to (\Delta\pi)_{\ell=2}$	unseen	55	29	$5D^2/216$
$N(1520, 3/2^-) \to N\pi$	70 ± 20	$\Gamma(1520) + 0.5\ \Gamma(1700) = 79$ (input)	$\simeq 75$ [f]	$D^2/54$ [f]
$N(1700, 3/2^-) \to N\pi$	$\simeq 13$ [g]		$\simeq 7$	$D^2/2160$
$N(1520, 3/2^-) \to (\Delta\pi)_{\ell=2}$	10 ± 6	$\Gamma(1520) + 0.243\ \Gamma(1700) = 30$	$\simeq 3$	$D^2/54$
$N(1700, 3/2^-) \to (\Delta\pi)_{\ell=2}$	unseen		$\simeq 15$	$4D^2/135$
$N(1535, 1/2^-) \to (\Delta\pi)_{\ell=2}$	unseen	$\Gamma(1535) + 0.264\ \Gamma(1715) = 35$	0.7 [h]	$D^2/216$ [h]
$N(1700, 1/2^-) \to \Delta\pi$	(i)		64	$D^2/24$
$\Delta(1650, 1/2^-) \to \Delta\pi$	52 ± 20	81	35	$5D^2/108$
S waves				
$\Delta(1670, 3/2^-) \to (\Delta\pi)_{\ell=0}$	172 ± 60	61	183	$5S^2/216$
$N(1520, 3/2^-) \to (\Delta\pi)_{\ell=0}$	$\simeq 15$	$\Gamma(1520) + 0.243\ \Gamma(1700) = 46$	30	$S^2/54$
$N(1700, 3/2^-) \to (\Delta\pi)_{\ell=0}$	$\simeq 17$ [j]		482	$5S^2/108$
$N(1535, 1/2^-) \to N\pi$	20 ± 20	$\Gamma(1535) + 0.505\ \Gamma(1700) = 116$ (input)	31	$S^2/432$
$N(1700, 1/2^-) \to N\pi$	70 ± 60		261	$S^2/48$
$\Delta(1650, 1/2^-) \to N\pi$	50 ± 10	18	29	$S^2/432$

[a] (Gilman, 1973b, e) (hyperon predictions by the author).

[b] (Faiman, 1972) except $N(3/2^-)$ values. In accord with (Petersen, 1972; Rosner, 1972c as quoted by Lovelace, 1972; and Petersen, 1973b).

[c] Partial width before correction for kinematic factor.

[d] As quoted by (Lasinski, 1973) or (Samios, 1973) here and below unless otherwise noted. πN widths are those quoted by (Lovelace, 1972) as average of (Almehed, 1972) and (Ayed, 1972); errors are our estimates.

[e] $\Delta\pi$ widths are quoted from (Gilman, 1973b, e) (with errors) or (Cashmore, 1973a) (without errors). Based on (Herndon, 1972).

[f] Numbers for $N(3/2^-)$ based on assigning N(1520) to (8, 2) and N(1700) to (8, 4).

[g] Based on (Ayed, 1972). Not seen by (Almehed, 1972).

[h] Numbers for $N(1/2^-)$ based on mixing such that $N(1700) \not\to N\eta$. This maximizes the $N\eta$ width of N(1535), as seems required (Faiman, 1972).

[i] This decay may have been observed in a new solution quoted by (Cashmore, 1973b).

[j] Substantially broader in new solution of (Cashmore, 1973b).

TABLE XIX

Some results of $SU(6)_W$ (with the new selection rules) which also follow from coplanar $SU(3) \times SU(3)$.

Prediction		Experiment	Remarks
$\frac{\Gamma(A_2 \to \rho\pi)}{\Gamma(A_2 \to \eta\pi)} =$	$\left\{\begin{matrix} 4.5 \text{ PCAC} \\ 2.7\ P^{*2\ell+1} \end{matrix}\right\}$ a	4.7 ± 0.5	$\tilde{\Gamma}(\rho\pi)/\tilde{\Gamma}(\eta\pi) = 9$ (See Table XVI)
$\Gamma(\Delta \to N\pi) \cong$	$\left\{\begin{matrix} 125 \text{ MeV (PCAC)} \\ 56 \text{ MeV } (P^{*2\ell+1}) \end{matrix}\right\}$	$\simeq$ 115 MeV	Eq. (VI. 23) Eq. (VI. 14)
f values	$1/2^+$: 0.4	0.3 to 0.4	See Table IV and text Section II. B. 3c
	$5/2^-$: -0.5	$\simeq$ -.15	
	$5/2^+$: 0.4	$\simeq$ .46	
Phases in $\pi N \to \pi\Delta$ (Fig. 32)	N(1470) (PP11) +	-	Below gap: See text Section VI. D
	N(1670) (DD15) +	+	
	(DG15) 0	0	See (Haut, 1973)
	N(1750) (PP11) -	+	See text, VI. D
$\frac{\Gamma[N(1670, 5/2^-) \to \Delta\pi]}{\Gamma[N(1670, 5/2^-) \to N\pi]} =$	$\left\{\begin{matrix} 3.9 \text{ (PCAC)} \\ 1.5\ (P^{*2\ell+1}) \end{matrix}\right.$	1.4 ± 0.5	$\tilde{\Gamma}(\Delta\pi)/\tilde{\Gamma}(N\pi) = 14$ (See Table XVIII

[a] If one uses the $P^{*2\ell+1}$ factor, one predicts also $\Gamma(A_2 \to \rho\pi)/\Gamma(A_2 \to K\bar{K}) \simeq \tilde{\Gamma}(A_2 \to \rho\pi)/\tilde{\Gamma}(A_2 \to K\bar{K}) = 6$. Experimentally this ratio is probably at least twice that value; see (Lasinski, 1973; Chaloupka, 1973).

TABLE XX

Relations among decays of $\underline{35}$, L=1 mesons in coplanar and chiral SU(3) × SU(3). [a]

Coplanar [b]	Chiral [c]
$g_1(A_2 \to \pi^-\rho^+) - g_1(A_1 \to \pi^-\rho^+) = \sqrt{2}\, g_0(B \to \pi^-\omega)$	$g_1(A_2 \to \pi^-\rho^+) + g_1(A_1 \to \pi^-\rho^+) = -\sqrt{2}\, g_1(B \to \pi^-\omega)$
$g_0(A_1 \to \pi^-\rho^+) = -\sqrt{2}\, g_1(B \to \pi^-\omega)$	$g_0(A_2 \to \pi^-\eta) + \sqrt{2}\, g_0(\delta \to \pi^-\eta) = g_0(A_1 \to \pi^-\rho^+)$
$g_1(A_2 \to \pi^-\rho^+) = \frac{3}{2}\, g_0(A_2 \to \pi^-\eta)$	
Common to both:	
$\sqrt{2}\, g_0(A_2 \to \pi^-\eta) - g_0(\delta \to \pi^-\eta) = g_0(B \to \pi^-\omega)$	
Combined[a]:	
$g_1(A_2 \to \pi^-\rho^+) = -\sqrt{3}\, D/8$	$g_0(A_1 \to \pi^-\rho^+) = \sqrt{3}\,(S-D)/12$
$g_0(A_2 \to \pi^-\eta) = -\sqrt{3}\, D/12$	$g_1(A_1 \to \pi^-\rho^+) = \sqrt{3}\,(2S+D)/24$
$g_0(\delta \to \pi^-\eta) = \sqrt{6}\, S/24$	$g_0(B \to \pi^-\omega) = -\sqrt{6}\,(S+2D)/24$
	$g_1(B \to \pi^-\omega) = -\sqrt{6}\,(S-D)/24$

[a] Phases of (Gilman, 1973e). g_λ are helicity amplitudes before correction by kinematic factors.

[b] (Rosner, 1972a).

[c] (Hey, 1973a).

TABLE XXI

Degeneracies of non-Pomeron trajectories from scattering of pseudoscalar mesons off one another.

Process	Degeneracy
$\pi\pi$ elastic	$f_0 - \rho$
πK elastic	$f_0 - \rho$
KK, $\bar{K}K$ elastic	$f_0 - \rho - A_2 - \omega$; $f' - \phi$
$\pi K \to K\pi$	$K^{**} - K^{*}$

TABLE XXII

Degeneracies for various meson-meson scattering processes.

Process	Degeneracy pattern $\tau=+$	$\tau=-$	Consequence
$PP \to PP$	$(1+8)(2^{++})$ <=>	$8(1^{--})$	Partial nonet symmetry. ["Ideal" nonets if $m_\phi > m_\rho \approx m_\omega$, $m_{f'} > m_f \simeq m_{A_2}$ assumed; see (Chiu, 1968).]
$PV \to VP$ and $PP \to VV$	$8(2^{++})$ <=>	$(1+8)(1^{--})$	"Ideal" nonet when combined with $PP \to PP$
	$8(0^{-+})$ <=>	$(1+8)(1^{+-})$	Pseudoscalars an octet; B belongs to a nonet
	$(1+8)(2^{--})$ <=>	$8(1^{++})$	A_1 and D belong to an octet, 2^{--} states a nonet.
$VV \to VV$	$(1+8)(0^{-+})$ <=>	$8(1^{+-})$	Pseudoscalars a <u>nonet</u>,
	$(8)(2^{--})$ <=>	$(1+8)(1^{++})$	A_1 and D in a <u>nonet</u>.

TABLE XXIII

Expected properties of some $\underline{70}$, L=2 and $\underline{56}$, L=3 members. From (Rosner, 1973a).

Resonance	Decay Mode	Partial Width MeV
$\underline{70}$, L=2		
N(~ 1950)	$N\pi$	13
	$\Delta\pi$	80[a]
Λ(~2100)	$N\bar{K}$	≈ 0
	$\Sigma\pi$	22
	$\Sigma(1385)\pi$	61[a]
$\underline{56}$, L=3		
Δ(~2200)	$N\pi$	8 - 32 MeV[b]
	$\Delta\pi$	3 - 11 MeV[b]

[a]If $\Gamma[\Delta(1950) \rightarrow \Delta\pi] = 100$ MeV. Otherwise these numbers represent percentages of $\Gamma[\Delta(1950) \rightarrow \Delta\pi]$. See the discussion of experimental values for this last number in section VI.C.

[b]Dependent on a free parameter. See (Minkowski, 1972).

TABLE XXIV

Helicities in resonance decays to $\pi\Delta_\lambda$

Resonance	$\Gamma(\lambda=3/2)/\Gamma(\lambda=1/2)$ (Herndon, 1972; Mehtani, 1972)	Partial Waves	Remarks
N(1470, $1/2^+$)	0	P	
N(1520, $3/2^-$)	> 1	S, D	
Δ(1650, $1/2^-$)	0	D	
Δ(1670, $3/2^-$)	1	S	D possible, absent $\Delta L_z = \pm 1$ predicts $\lambda = 3/2$ dominant
N(1670, $5/2^-$)	6	D	G possible, absent
N(1690, $5/2^+$)	2/3	P (see text)	F possible, absent
N(1730, $3/2^-$)	1	S	D possible, absent $\Delta L_z = \pm 1$ predicts $\lambda = 1/2$ dominant
N(1750, $1/2^+$)	0	P	
Δ(1890, $5/2^+$)	1.5	F	See (Fung, 1973; Faiman, 1973a)
Δ(1910, $1/2^+$)	0	P	Weak signal
Δ(1950, $7/2^+$)	5	F	H possible, absent

TABLE XXV

Expected nonstrange members of the second positive-parity group of baryon resonances, below ~2.1 GeV.

SU(6), L^P / L_{2I2J}	$\underline{56}$, 0^+	$\underline{70}$, 0^+	$\underline{56}$, 2^+	$\underline{70}$, 2^+	Remarks
P^*_{11}	$N\left(\frac{1}{2}^+, 1470\right)$	$N\left(\frac{1}{2}^+, 1780\right)$	-	$N\left(\frac{1}{2}^+, ?\right)$	Unknown mixing effects
P^*_{13}	-	$N\left(\frac{3}{2}^+, ?\right)$	$N\left(\frac{3}{2}^+, 1850\right)$	$N\left(\frac{3}{2}^+, ?\right)$	Unknown mixing effects
				$N\left(\frac{3}{2}^+, ?\right)$	For assignment of observed state, see (Petersen, 1973a)
F_{15}	-	-	$N\left(\frac{5}{2}^+, 1690\right)$	$N\left(\frac{5}{2}^+, ?\right)$	Bounds on mixing exist
				$N\left(\frac{5}{2}^+, ?\right)$	Possible additional state observed; see (Faiman, 1973a)
F_{17}	-	-	-	$N\left(\frac{7}{2}^+, \sim 2025\right)$	Needs confirmation
P_{31}	-	$\Delta\left(\frac{1}{2}^+, ?\right)$	$\Delta\left(\frac{1}{2}^+, 1910\right)$	-	Unknown mixing effects
P_{33}	$\Delta\left(\frac{3}{2}^+, ?\right)$	-	$\Delta\left(\frac{3}{2}^+, ?\right)$	$\Delta\left(\frac{3}{2}^+, ?\right)$	A complete mystery. Effects at 1690, 1890?
F_{35}	-	-	$\Delta\left(\frac{5}{2}^+, 1890\right)$	$\Delta\left(\frac{5}{2}^+, ?\right)$	Bounds on mixing: (Faiman, 1973a)
F_{37}	-	-	$\Delta\left(\frac{7}{2}^+, 1950\right)$	-	The only unambiguous state

*Additional P_{11}, P_{13} states are expected in $\underline{20}$, $L^P=1^+$. [For possible evidence, see (Yaffe, 1973).] These would not couple to πN but could alter the mixing pattern based on the above table.

TABLE XXVI

Ratios of $\sigma(e^+e^- \to A+B)/\sigma(e^+e^- \to \pi^+\pi^-)$ in a naive SU(6) model.*

Type of final state		Specific final state	Ratio to $\pi^+\pi^-$
PP	a	$\to \pi^+\pi^-$	1 (definition)
	a	$\to K^+K^-$	1**
		$\to K^o\bar{K}^o$	0**
PV		$\to \rho^{\pm}\pi^{\mp}$	4/9
		$\to \rho^o\pi^o$	2/9
		$\omega\pi^o$	2
	a	$\to \rho^o\eta$	2/3
	a	$\to \phi\eta$	16/27**
		$\omega\eta$	2/27
		$\phi\pi^o$	0
		$\to K^{*+}K^- + c.c.$	4/9**
		$\to K^{*o}\bar{K}^o + c.c.$	16/9**
VV		$\rho^+\rho^-$	7
		$\to K^{*+}K^{*-}$	7**
		$K^{*o}\bar{K}^{*o}$	0**

$\to$: Particularly accessible final state (see text).

[a]May be distinguishable from one another via kinematic fitting.

* The model is based on the quark-pair creation picture of (Petersen, 1972, 1973a,b). Some of our results differ from those of (Ritson, 1972).

** : Involves creation of pair of strange quarks from the vacuum with same amplitude as for nonstrange quarks.

TABLE XXVII

Some useful final states involving neutrals in $\pi^+ p \to$ (anything)

Final state	Recoil baryon	Physics questions
$\pi^o \pi^o \pi^+ p$	Δ^{++}	$\pi^o \pi^o$: ϵ, ϵ'
	p	$\pi^o \pi^o \pi^+$: $A_1 \xrightarrow{?} \epsilon\pi$
$\eta^o \pi^o \pi^+ p$	Δ^{++}	$\eta^o \pi^o$: $\delta(970)$, A_2^o : mechanisms of production (B exchange ?)
	p	$\pi^o \eta \pi^+$: $B \to \delta(970)\pi$
$\eta^o \eta^o \pi^+ p$	Δ^{++}	$\eta^o \eta^o$: $\epsilon' \xrightarrow{?} \eta\eta$
$3\pi^o \pi^+ p$	Δ^{++}	$A_1, A_2 \to 3\pi^o$
	p	$B \to A_1 \pi$
$\eta\pi^o \pi^o \pi^+ p$	Δ^{++}	pure I=0 states in $\eta\pi^o\pi^o$ channel
$\pi^o \pi^o \pi^+ \pi^- \pi^+ p$	Δ^{++}	charge-exchange production of B; $B^o \to \omega^o \pi^o$
	p	$A_2^+ \to \begin{Bmatrix} B^+\pi^o \\ B^o\pi^+ \end{Bmatrix} \to \omega\pi^+\pi^o$

TABLE XXVIII

Some Questions to be Answered About Mesons in the Quark Model.

State	J^{PC}	Resonance	Question
$q\bar{q}$, L=1	0^{++}	δ (970)	Existence; width. Best experiment $\pi^- p \to \eta \pi^- p$, $\eta \to \gamma\gamma$
		ϵ, S^*, ϵ'	$\pi^0\pi^0$, $K\bar{K}\eta\eta$ decays
		K_N(1100-1400)	Existence, width. $K\pi$ scattering needed
	1^{++}	A_1	Existence; width
		D	J^P confirmation
		D'	Existence. Mass ~ 953 MeV? Could be E(1420) if $J^P(E) \neq 0^-$.
		$Q_A(K_A^*)$	Confirm non-diffractive production
	1^{+-}	B	Helicity of ω in $B \to \omega\pi$, new production mechanisms for B
		(I=0 states)	Both missing. If all $\rho\pi$ width concentrated in one state, this state should be three times as wide as the B! Visible only in partial-wave analyses: $\pi^- p \to \pi^-\pi^+\pi^0 n$, etc.
		$Q_B(K_A^*)$	Confirm non-diffractive production
	2^{++}	A_2	$B\pi$, $\omega\pi\pi$ couplings
		f_0	$\rho\rho$, $\gamma\gamma$ couplings
		f'	$K^*\bar{K}$ + c.c., $K\bar{K}$, $\gamma\gamma$ couplings
		K^{**}	Behavior of $K\pi$ spectrum above peak: reason for sharp drop-off
$q\bar{q}$; L=2	3^{--}	g ω_3	Inelastic couplings
		ϕ_3	Existence: $\to K\bar{K}$, $K^*\bar{K}$ + c.c. Expected mass: ~ 1820 MeV.
		K_N(1760)	Inelastic couplings
	2^{--}	"ρ-like" state	πA_2 s-wave effect?
		I=0 states G = -	Look for $B\pi$, $\omega\epsilon$, $\omega\eta$, $\phi\eta$ effects.
		K^*	Mixes with 2^{-+}: L(1770)? Structure in L peak
	2^{-+}	A_3	Resonant nature? $f_0\pi$ Deck effect a likely background
		I=0 states G = +	πA_2 s-wave effect
		K^*	Mixes with 2^{--}; L(1770)? Structure in L peak
	1^{--}	ρ'	Elasticity ($\pi\pi$ coupling); $\rho\epsilon$, πA_1 decays
		I=0 states	$\omega' \to \pi B$; $\phi' \to \eta D$, etc.
		K^*	Possibly visible in $K\pi$ scattering.

TABLE XXIX

Correspondence Between Nuclear and Hadronic Total Cross Sections.
All Energies are Lab. Kinetic Energies

Structure in σ_T (nC)	Energy Range	Interpretation	Structure in hadron σ_T	Energy Range	Interpretation
Constant	$T_n \leq$ 100 keV	Scattering length	Constant $\sigma_T(K^+p)$	$T_K \leq$ 400 MeV	Scattering length
Pronounced bumps; falling trend	1 - 10 MeV	Compound nucleus resonances	Bumps in $\sigma_T(\pi N)$	200 MeV to 2 GeV	Direct Channel resonances (DCR)
Rise	10 - 20 MeV	Inelastic Channels	Rise in σ_T(pp)	Peak at 1 GeV	Onset of pion production or N* excitation
Falling trend	20 - 300 MeV	σ_T(NN) falls	σ_T(AB) falls when AB non-exotic	2 to 25 GeV	Duality or falling $\sigma_T(q_i\bar{q}_i)$
Rise	300-1500 MeV	Onset of pion production or N* excitation	Rise in $\sigma_T(K^+p)$ σ_T(pp)	$\geq$ 25 GeV $\geq$ 200 GeV	?

TABLE D.1

SU(6) × SU(3) Factors for Decays to $1/2^+ 0^-$ states. A square root is to be understood between each sign and the corresponding number. Isospin Clebsch-Gordan coefficients are omitted.

N	56 (8,2)	70 (8,2)	70 (8,4)
$N\pi$	-5/18	1/6	-1/48
ΣK	1/90	1/96	1/12
$N\eta$	-1/90	1/24	1/48
ΛK	1/10	-3/32	0

Δ	56 (10,4)	70 (10,2)
$N\pi$	-4/45	-1/48
ΣK	4/45	1/48

Λ	56 (8,2)	70 (8,2)	70 (8,4)	70 (1,2)
$N\bar{K}$	-1/5	3/16	0	3/16
ΞK	-1/45	1/12	1/24	-3/16
$\Sigma\pi$	2/15	-1/32	-1/16	9/32
$\Lambda\eta$	2/45	-1/96	-1/48	-3/32

Σ	56 (8,2)	56 (10,4)	70 (8,2)	70 (8,4)	70 (10,2)
$N\bar{K}$	1/135	-4/135	1/144	1/18	-1/144
ΞK	5/27	4/135	-1/9	1/72	1/144
$\Sigma\pi$	-16/135	4/135	25/144	1/72	1/144
$\Sigma\eta$	-2/45	2/45	1/96	-1/48	1/96
$\Lambda\pi$	-2/45	-2/45	1/96	-1/48	-1/96

Ξ	56 (8,2)	56 (10,4)	70 (8,2)	70 (8,4)	70 (10,2)
$\Xi\pi$	1/90	2/45	1/96	1/12	1/96
$\Sigma\bar{K}$	-5/18	2/45	1/6	-1/48	1/96
$\Xi\eta$	1/10	2/45	-3/32	0	1/96
$\Lambda\bar{K}$	-1/90	-2/45	1/24	1/48	-1/96

Ω	56 (10,4)	70 (10,2)
$\Xi\bar{K}$	8/45	1/24

FIGURE CAPTIONS

1. Helicities and fraction of D-wave in $B \to \omega\pi$. The curve is based on Eq. (A.4). The relative phase of F_0 and F_1 is also measurable and allows one to exclude the upper branch of the curve. F_0/F_1 is assumed real.
2. Possible mechanisms for diffractive production of low-mass peaks corresponding to $\ell=0$ $\rho\pi$ or f_0 π systems. (a) Deck mechanism: a forward-scattered pion near its mass shell is often in an S-wave low-mass state relative to the ρ or f_0. (b) True A_1 or A_3 resonance production.
3. New information on the I=J=0 amplitude in $\pi\pi$ scattering. (a) S-wave I=0 Argand diagram from (Protopopescu, 1973), as quoted by (Diebold, 1972). (b) Argand diagrams for S-wave (I=0), P-wave (I=1), and D-wave (I=0) in $\pi\pi$ scattering, from (Estabrooks, 1973). (c) Comparison of δ_0^o from two solutions of (Estabrooks, 1973) with that of (Protopopescu, 1973). (d) Qualitative behavior of new solutions for δ_0^o in comparison with old "up" and "down" solutions, for $m_{\pi\pi} \geq m_\rho$. (e) $\pi^o\pi^o$ mass spectrum quoted by (Estabrooks, 1973), favoring their solution 1.
4. $\eta\pi$ mass spectrum of (Conforto, 1973) obtained in $\pi^-(4.5\ \mathrm{GeV/c}) + p \to \eta\pi^- p \to \gamma\gamma\pi^- p$. The dotted line corresponds to a Monte Carlo estimate of phase space background combined with geometrical acceptance. The fitted parameters are $M = 980 \pm 1$, $\Gamma = 60\,^{+50}_{-30}$ MeV, and the inferred cross section is $1.8 \pm 0.8\ \mu b$.
5. Result of fit to decay rates of $3/2^+$ baryons (Samios, 1973). Arrows show range of variation of SU(3)-invariant amplitude A_{10}. Pattern of SU(3) breaking is clearly visible, but statistical significance doubtful. Here $\chi^2 = 7.8$ for 3 degrees of freedom, while for a similar fit of (Barbaro-Galtieri, 1972), $\chi^2 = 24.0$ as a result of assigning smaller errors.

6. Values of $\chi = (\Gamma_{exp} - \Gamma_{SU(3)})/\Delta\Gamma$ versus f from the fits of (Samios, 197
(a) Decays $1/2^- \rightarrow 1/2^+0^-$: N(1531), $\Lambda_8(1675)$, $\Lambda_1(1402)$, $\Sigma(1774)$. The subscripts denote the major SU(3) representation in each (mixed) Λ state.
(b) Decays $3/2^- \rightarrow 1/2^+0^-$: N(1520), $\Lambda_8(1690)$, $\Lambda_1(1518)$, $\Sigma(1671)$.
(c) Decays $7/2^- \rightarrow 1/2^+0^-$: N(2184), $\Lambda_8(2350)$ if $J^P = 7/2^-$ rather than 9/ $\Lambda_1(2099)$, $\Sigma(2252)$. (d) Decays $5/2^- \rightarrow 1/2^+0^-$: N(1674), $\Lambda(1829)$, $\Sigma(1767)$
(e) Decays $5/2^+ \rightarrow 1/2^+0^-$: N(1687), $\Lambda(1817)$, $\Sigma(1927)$.

7. SU(3) fit of (Samios, 1973) to $7/2^+$ decays: $\Delta(1931)$, $\Sigma(2031)$.

8. Backward π^+p elastic cross section: preliminary data of (Baker, 1972). solid line is a fit including a $\Delta(2160)$; the dashed line is a fit without this s

9. Forward differential cross section for $\pi^-p \rightarrow n\pi^0$ compared with predictioı of forward dispersion relations (from Nelson, 1973a). Solid curve: dispersion relation calculation of (Hohler, 1971). Dashed curve: dispersion relation calculation of (Carter, 1973).

10. Resonant particles in the "Tables of Particle Properties," as compiled by the Particle Data Group (Lasinski, 1973 and earlier references), as a function of time.

11. Exotic resonances in the "Tables" as a function of time.

12. $\sigma_T(K^+N)$ for I=0 from (Carroll, 1973a). References are given there.

13. Completion of baryonic SU(3) multiplets. The J^P is shown to the right of each level. A wavy line indicates a level that is uncertain. (All N, Δ, Λ, and Σ levels are based on direct-channel phase shift analyses.) A dashec line is one predicted by the rough formula $M_R = m_{N \text{ or } \Delta} - (150 \text{ MeV})\, Y$. If a level is observed within ~ 100 MeV of the predicted value, its actual value is shown. Deviations from the Gell-Mann-Okubo formula are much

smaller than this, of course. In deciding whether a line should be wavy or solid we generally use the same criteria as (Lasinski, 1973) for inclusion in the Tables of Resonant Particles. A parenthesis around J^P values (for Ξ states) indicates ones assumed on the basis of the Gell-Mann-Okubo mass formula, where the Ξ is need to complete an octet.

14. Completion of mesonic SU(3) multiplets. The J^{PC} is shown to the right of each level. Solid, wavy, and dashed lines are as in Fig. 13. The rules for guessing the masses of missing states are indicated in the text. Predictions for I=Y=0 states are extremely uncertain because of the probability of arbitrary octet-singlet mixing (which occurs in the known cases).

15. Signs of resonant amplitudes in $1/2^+ \, 0^- \rightarrow 1/2^+ \, 0^-$. The baryon-first convention has been used as in (Lasinski, 1973). Signs are to be multiplied by those of isospin Clebsch-Gordan coefficients for specific reactions. The f/d values expected from $SU(6)_W$ for unmixed octets are -1/3 (i.e., f=-1/2) for $\underline{70}(8,4)$; +2/3 (i.e., f=2/5) for $\underline{56}(8,2)$; and +5/3 (i.e., f=5/8) for $\underline{70}(8,2)$.

16. Quality of SU(3) fits obtained by (Samios, 1973) for decays of $J^P = 2^+$ mesons. (a) Final states 0^-0^-. Abscissa denotes magnitude of d-type SU(3) amplitude $|A_s|$. (b) Final states 1^-0^-. Abscissa denotes magnitude of f-type SU(3) amplitude $|A_a|$.

17. Parity alternation for baryon resonances. Number of states with given parity shown for each interval of m^2. Masses are corrected for SU(3) breaking by subtracting 150 MeV per unit of $|S|$.

18. Parity alternation for meson resonances. SU(3) breaking handled as in Fig. 17.

19. (a) Model for resonance dominance of $\sigma(e^+e^- \to \text{hadrons})$. (b) Wiggles in σ predicted from resonance dominance and parity alternation.

20. Evidence for baryonic straight-line trajectories. Central points and error bars are values of $M^2 \pm \Gamma M$ quoted by (Lasinski, 1973). (a) Nucleon trajectory. (b) Λ trajectory. Intercept obtained from $K^+p \to pK^+$ and $\bar{p}p \to K^-K^+$ (see, e.g., Hovjat, 1973). (c) Δ trajectory. Intercepts of N and Δ from (Barger, 1972).

21. Evidence for mesonic straight-line trajectories. (a) ρ trajectory. Intercept from πN CEX. Total cross section differences give nearly .7, however. (b) ω trajectory. Intercept based on $\sigma_T(K^-p) - \sigma_T(K^+p)$ and $\sigma_T(\bar{p}p) - \sigma_T(pp)$.

22. Formation of first resonances above threshold in non-exotic channels (symbolized by quark graphs). Number of cases are plotted against c.m. 3-momentum magnitude P* for (a) meson-meson, and (b) meson-baryon systems. Each isospin channel is treated separately. The letter in the upper right hand corner of each box indicates the partial wave in which the resonance is formed.

23. Plot of (I_3, Y) for quarks. The triplet (u, d, s) is often referred to as (p, n, λ) or $(\mathscr{P}, \mathscr{N}, \lambda)$.

24. Levels of resonances in the L-excitation quark model for which there exists substantial evidence. (a) Mesons; (b) baryons. The boxed numbers refer to observed J^P values.

25. Assignment of baryon resonances in Fig. 17 to multiplets of SU(6) $\times$ 0(3). (a) Second $\underline{56}$, $L^P=0^+$ ("radial excitation"). (b) Possible $\underline{70}$, $L^P=0^+$. (c) $\underline{70}$, $L^P=2^+$. (d) $\underline{70}$, $L^P=3^-$. Recall that masses have been altered from those of the actual levels (Fig. 13) by subtracting 150 MeV for each unit of negative hypercharge.

26. Assignment of meson resonances in Fig. 18 to multiplets of $SU(6)_q \times SU(6)_{\bar{q}} \times 0(3)$. (a) Second $(6,\bar{6})$, $L^P = 0^-$. Masses altered from those of actual levels (Fig. 14) by subtracting 150 MeV for kaonic states.

27. "Box score" for filling the major multiplets of $SU(6)_q \times 0(3)$ with observed baryons. The m^2 scale is very rough; exact masses of levels are given in Fig. 13. Mixing among states is possible; in this case the assignments to specific SU(3) representations are educated guesses based on masses and couplings. Blank spaces enclosed in heavy lines denote missing states. States with same (I, Y) are listed vertically; states with same J^P are listed horizontally.

28. "Box score" for filling the major meson $(6,\bar{6})$, L multiplets of $SU(6)_q \times SU(6)_{\bar{q}} \times 0(3)$.

29. Lowest hadronic levels predicted by a harmonic-oscillator quark model. The principal quantum number N denotes the total number of oscillator excitations. (a) Baryons. Numbers indicate dimension of $SU(6)_q$ multiplets, with superscripts denoting parity. Multiplets in parentheses cannot couple to ground-state baryons in a single-quark-transition picture. Check marks denote multiplets for which candidates exist; question marks denote multiplets for which very speculative assignments may be made. (b) Mesons. All multiplets are $(6,\bar{6})$, with superscripts denoting parity. Candidates for all multiplets exist, as noted by check marks.

30. Quark graphs describing hadronic vertices. (a) Examples of connected graphs. (b) Examples of disconnected graphs.

31. Argand circles in $\pi N \to \pi\Delta$, from (Herndon, 1972) (on left) and absolute squares of partial-wave amplitudes (on right). Solid lines denote results of resonance fits; letters denote experimental points in increasing

alphabetical order with respect to c.m. energy, e.g., H = 1440 MeV, L = 1540 MeV, P = 1650 MeV, T = 1770 MeV, X = 1930 MeV. Note the existence of a gap between 1540 and 1650 MeV.

32. (a) Phases of resonant amplitudes in $\pi N \rightarrow \pi\Delta$ (crosses, from Herndon, 1972) along with symmetry predictions (arrows, from Faiman, 1973b). Shown are "anti-$SU(6)_W$" predictions, corresponding to $\Delta L_z = \pm 1$ dominanc For "$SU(6)_W$-like" predictions ($\Delta L_z = 0$ dominance), reverse all signs of double-headed arrows. (b) Predictions for all multiplets expected below 2 GeV. (Faiman, 1973b)

33. Comparison of photoproduction helicity amplitudes with sign predictions of (Gilman, 1973d). The normalization is such that $\Gamma[R \rightarrow (P \text{ or } N)\gamma] \sim \left|A_{1/2}^{P,N}\right|^2 + \left|A_{3/2}^{P,N}\right|^2$. The subscript denotes the total helicity of the nucleon-γ system. $SU(6) \times 0(3)$ assignments are shown on the left. Letters next to J^P of resonances denote final πN partia waves. Lengths of arrows denote predicted magnitudes. A check mark denotes agreement in sign, a cross, disagreement, and a zero, a predicte vanishing of the amplitude. Predictions for A_λ^N for Δ resonances are the same as those for A_λ^P and hence are not shown. (a) $\underline{56}$, L=0 and $\underline{70}$, L=1 multiplets. (b) $\underline{56}$, L=2; (radially excited) $\underline{56}$, L=0; and (presumed) $\underline{70}$, L=0 multiplets. Notes: (a) estimated from real parts; (b) trouble in the quark model (Moorhouse, 1973c).

34. Graphs for estimating energy dependence of total cross sections in the range 6 - 30 GeV. A falling total cross section in this range is assumed to reflect substantial non-Pomeron exchange contributions to the forward elastic imaginary part. (a), (c), (e) falling total cross sections; (b), (d), (f) flat total cross sections. The mnemonic is due to (Lipkin, 1966c).

35. Duality graphs for baryon-antibaryon scattering. (a) s-channel exotic, t-channel non-exotic. (b) s-channel non-exotic, t-channel exotic.

36. Graph for decay of a "gallon" to another "gallon" plus an ordinary $q\bar{q}$ meson, allowed by the selection rules of (Freund, 1969a).

37. (a) Three-quark picture of baryons. Note the two degrees of freedom associated with ℓ_{12}, ℓ_3. This leads to an infinitely-degenerate leading trajectory. (b) Characteristic $SU(6)_W \times 0(3)$ multiplets of the quark-model solution to duality for baryons. Also shown are characteristic states of multiplets which need confirmation.

38. Zero contours in the Mandelstam plane for the real part of the $\pi^+\pi^- \rightarrow \pi^+\pi^-$ amplitude. (Estabrooks, 1973) The contour z_1 has been ascribed to the on-shell appearance of the (Adler, 1965a) zero (Pennington, 1972), while z_2 is the presumed Odorico zero. (Odorico, 1970-3.)

39. Mandelstam plane plot of differential cross section dips for $\bar{p}p \rightarrow \pi^-\pi^+$ and crossed processes. (Parsons, 1973.) The zero near t=0, corresponding to a dip in backward $\pi^+p \rightarrow \pi^+p$ and in forward $\bar{p}p \rightarrow \pi^-\pi^+$, is assumed to be associated with the intersection of the $\rho(765)$ and $\Delta(1236)$ poles in s and u, respectively.

40. Model for 0^+ mesons incorporating both an approximately "ideal" nonet of quark model $^3P_0$ states and a unitary singlet dilaton of lower mass. The mixing effects are assumed to be small, giving rise to drastic alterations in couplings as a result of a large intrinsic coupling of the dilaton to pseudo-scalar pairs.

41. Data available in inelastic πN channels at low energies. (a) $\pi N \rightarrow N\eta$ differential cross sections, as used in the analysis of (Deans, 1971). Not included are points from (Lemoigne, 1973) and (Chaffee, 1973).

(b) $\pi N \rightarrow \Lambda K$ differential cross sections and (generally) polarizations, as used and quoted by (Wagner, 1971a). (c) $\pi N \rightarrow \Sigma K$. Lines denote bins used by (Langbein, 1973). Specific gaps are illustrated at right by open circles. σ: differential cross section; P: polarization. Superscripts +, o, - refer to $\pi^+ p \rightarrow K^+\Sigma^+$, $\pi^- p \rightarrow K^o\Sigma^o$, or $\pi^- p \rightarrow K^+\Sigma^-$. *: new polarizations in $\pi^+ n \rightarrow K^o\Sigma^+$ from (Davies, 1973). No P^- available except at point a).

42. Pion photoproduction data in the resonance region used in the analysis of (Moorhouse, 1973c). ●: "good" data; ⊖: "fair" data, O: poor data. π^+: $\gamma p \rightarrow \pi^+ n$; π^o: $\gamma p \rightarrow \pi^o p$; π^-: $\gamma n \rightarrow \pi^- p$. σ: differential cross section; A: polarized photon asymmetry; P: recoil nucleon polarization; T: polarized target.

43. Model for hadron production by virtual photon in colliding e^+e^- experiments. (a) Production of meson pair. (b) Production of many mesons.

44. Two-photon process for hadron production in colliding lepton beams.

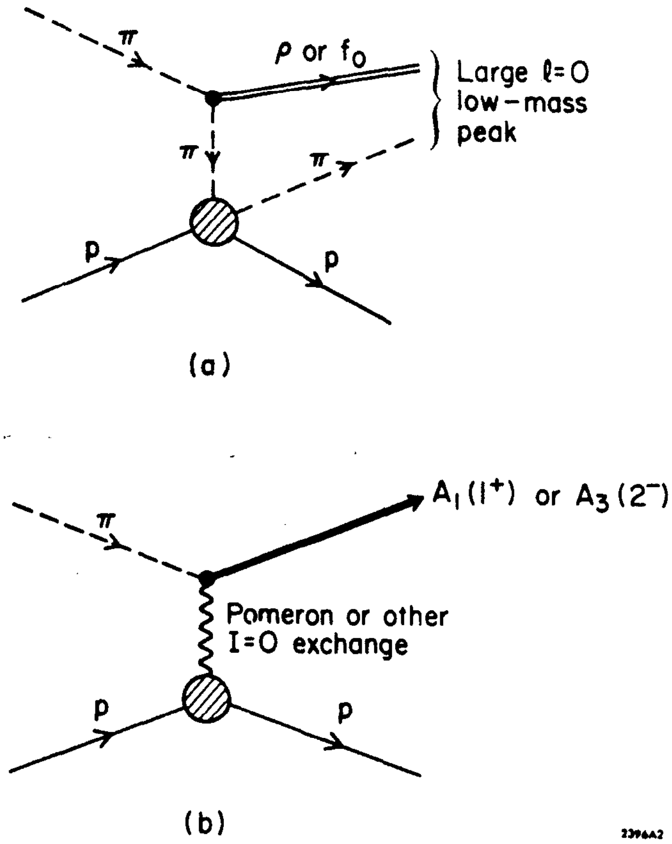

π
ρ or f_0
Large ℓ=0
low-mass
peak
π
π
p
p
(a)
π
$A_1(1^+)$ or $A_3(2^-)$
Pomeron or other
I=0 exchange
p
p
(b)

Fig. 1

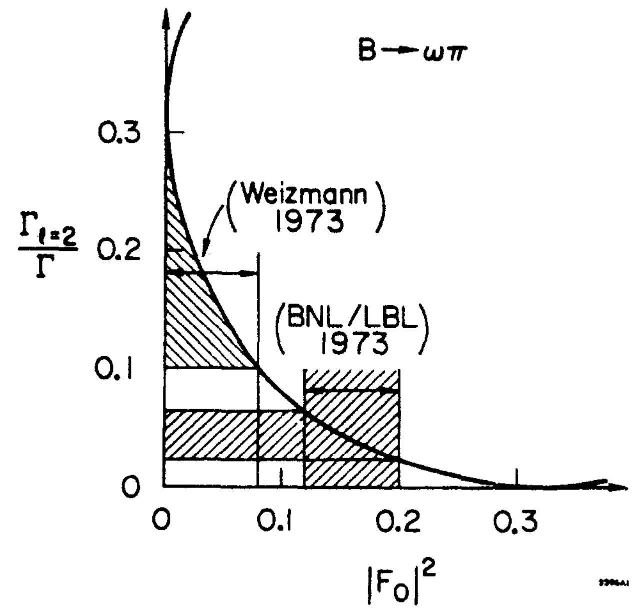
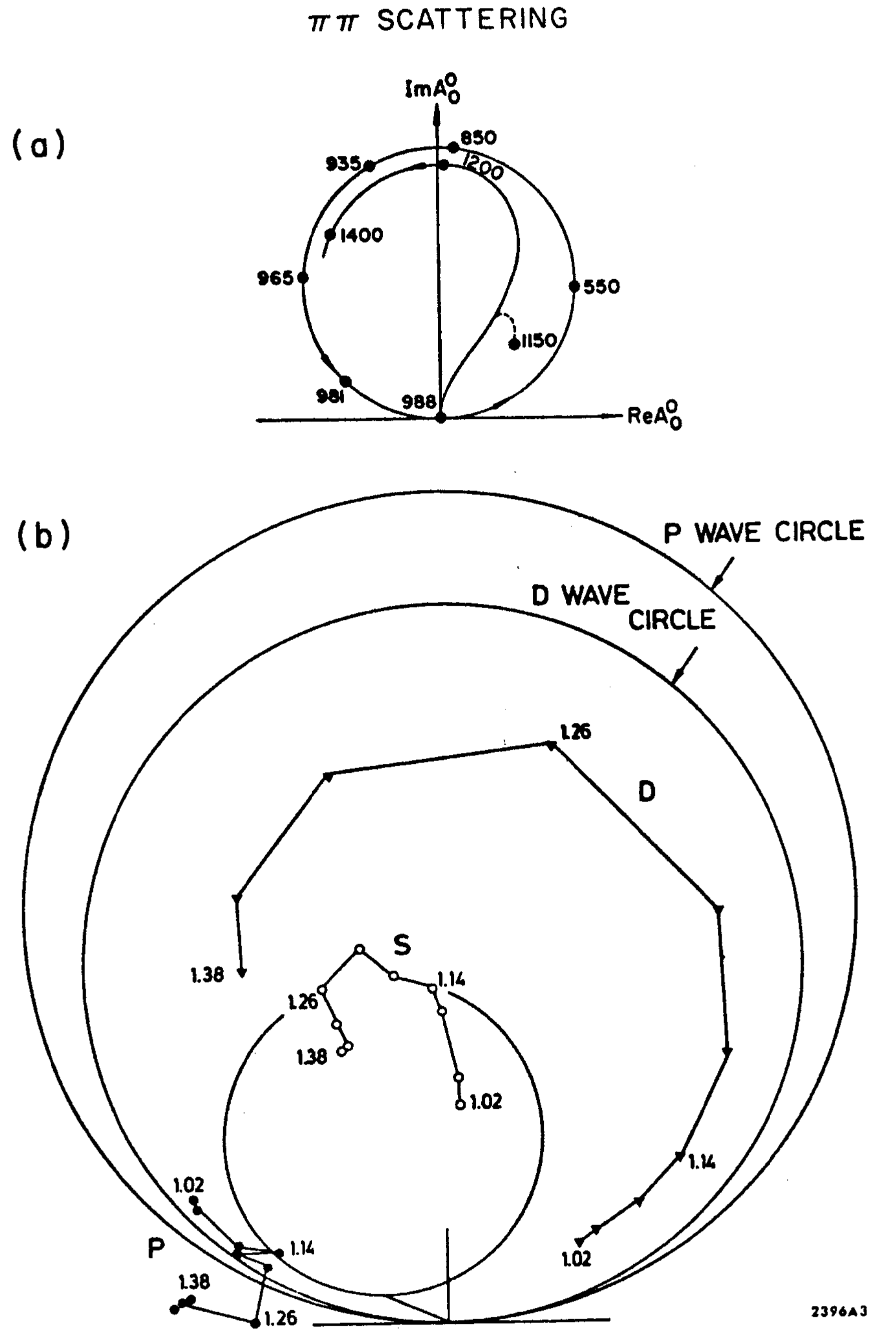
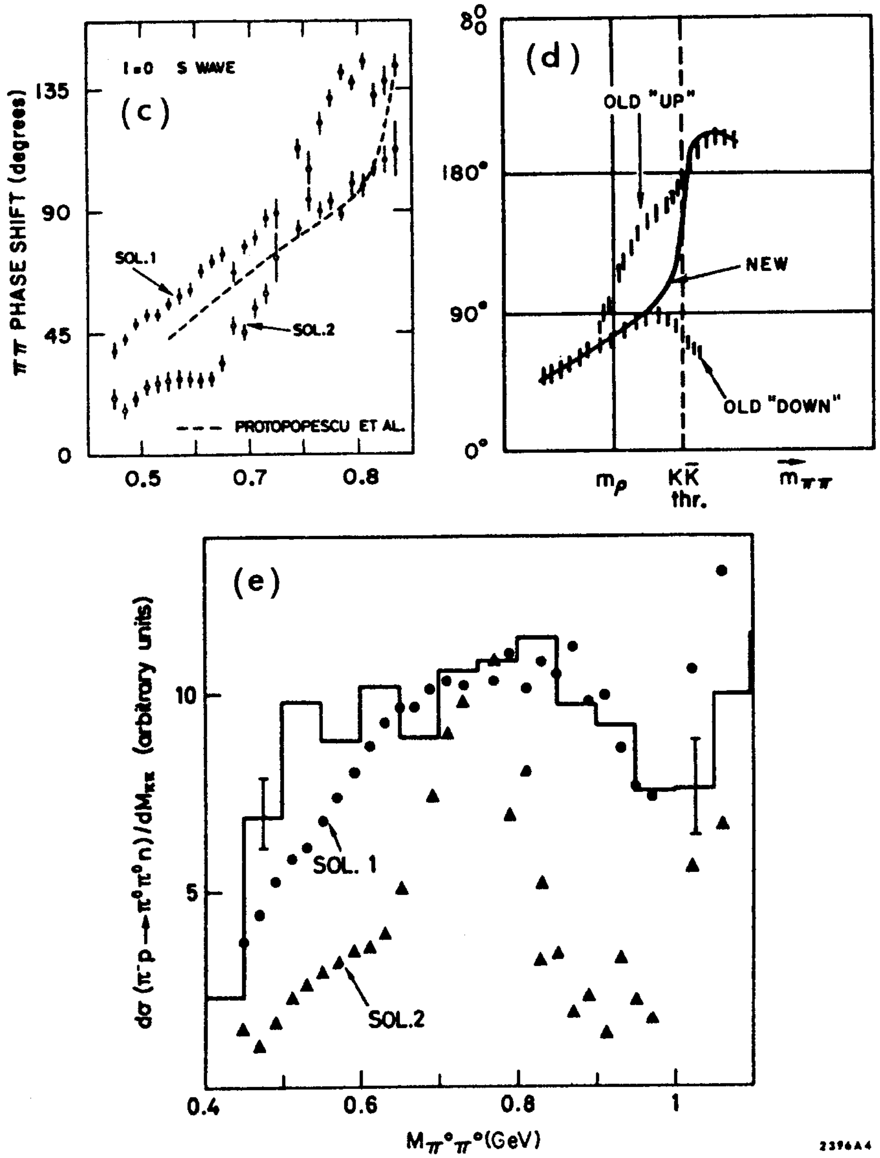

B → ωπ
0.3
$\frac{\Gamma_{\ell=2}}{\Gamma}$
0.2
0.1
0
(Weizmann 1973)
(BNL/LBL 1973)
0
0.1
0.2
0.3
$|F_0|^2$

Fig. 2



ππ SCATTERING
(a)
ImA_0^0
ReA_0^0
850
1200
935
1400
965
550
1150
981
988
(b)
P WAVE CIRCLE
D WAVE CIRCLE
1.26
D
1.38
S
1.14
1.26
1.38
1.02
1.14
1.02
1.14
P
1.38
1.26
1.02
2396A3



I=0 S WAVE
(c)
ππ PHASE SHIFT (degrees)
135
90
45
0
SOL. 1
SOL. 2
--- PROTOPOPESCU ET AL.
0.5
0.7
0.8
δ_0^0
(d)
OLD "UP"
180°
NEW
90°
OLD "DOWN"
0°
m_ρ
$K\bar{K}$ thr.
$\vec{m}_{\pi\pi}$
(e)
$d\sigma(\pi^- p \to \pi^0\pi^0 n)/dM_{\pi\pi}$ (arbitrary units)
10
5
SOL. 1
SOL. 2
0.4
0.6
0.8
1
$M_{\pi^0\pi^0}$(GeV)
2396A4

Fig. 3

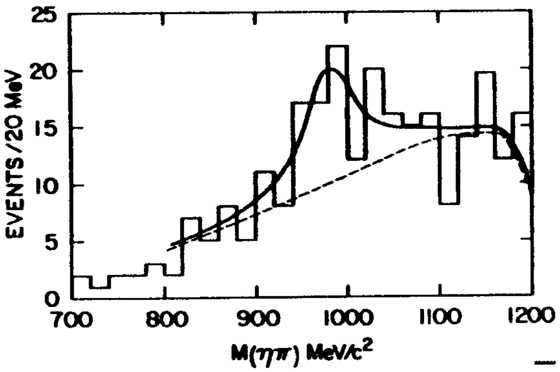


Fig. 4

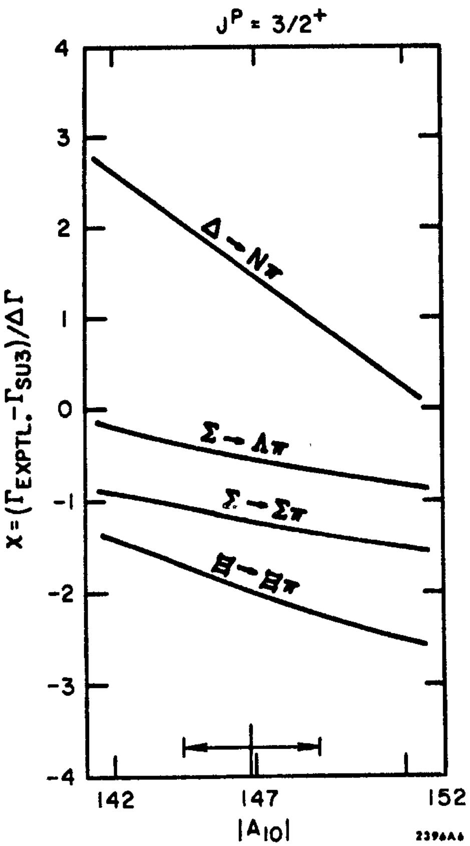


Fig. 5

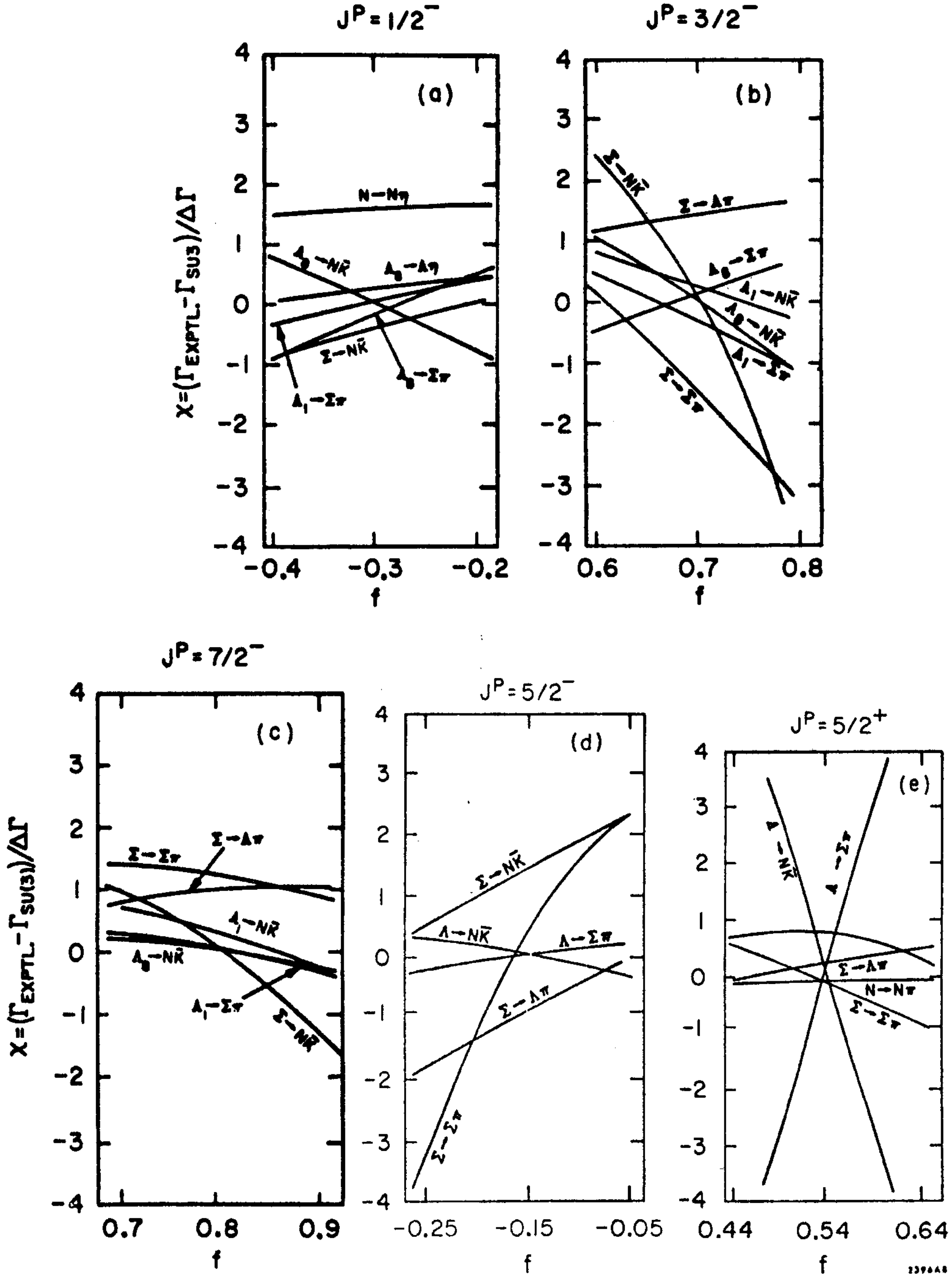


Fig. 6

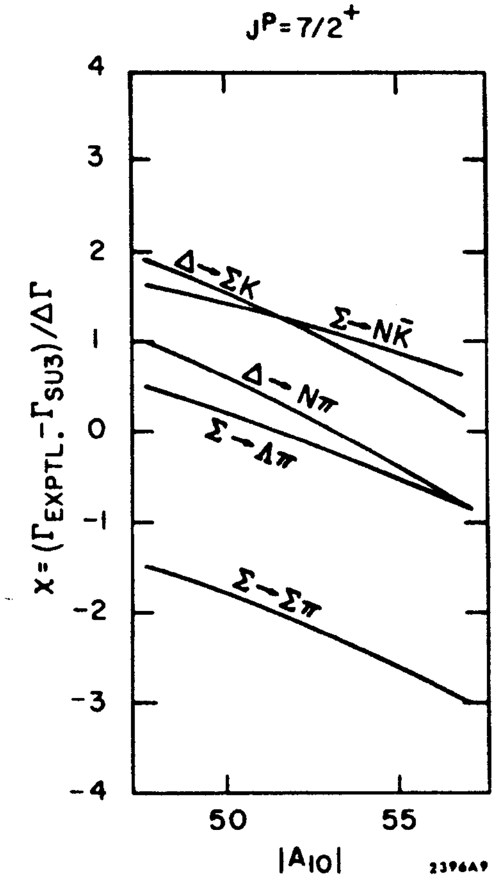

$J^P = 7/2^+$
4
3
2
1
0
-1
-2
-3
-4
$\chi = (\Gamma_{EXPTL.} - \Gamma_{SU3})/\Delta\Gamma$
$\Delta \to \Sigma K$
$\Sigma \to N\bar{K}$
$\Delta \to N\pi$
$\Sigma \to \Delta\pi$
$\Sigma \to \Sigma\pi$
50
55
$|A_{10}|$

Fig. 7

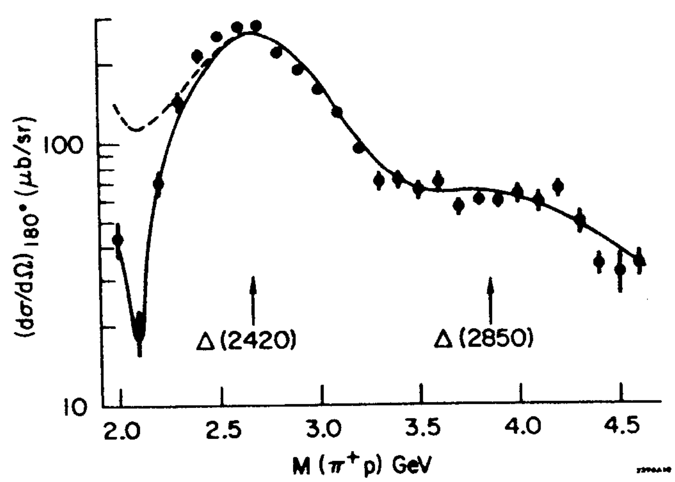
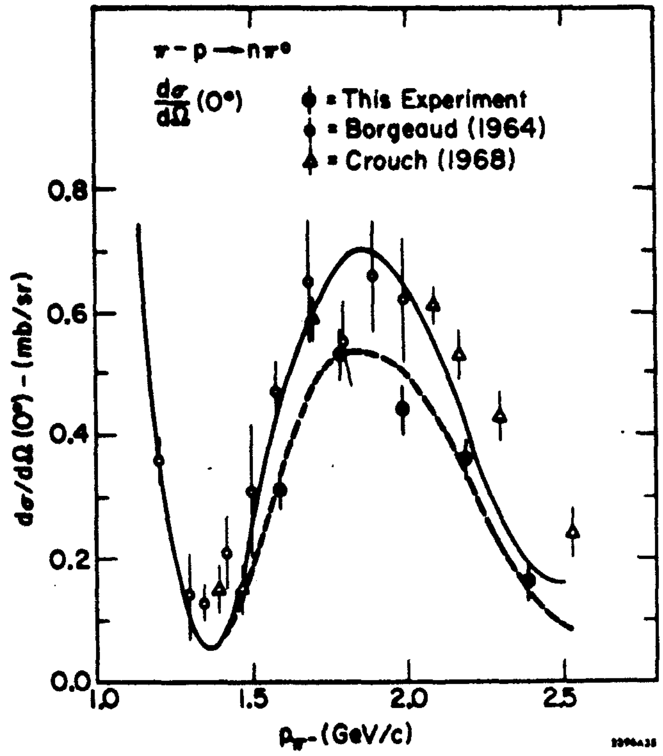
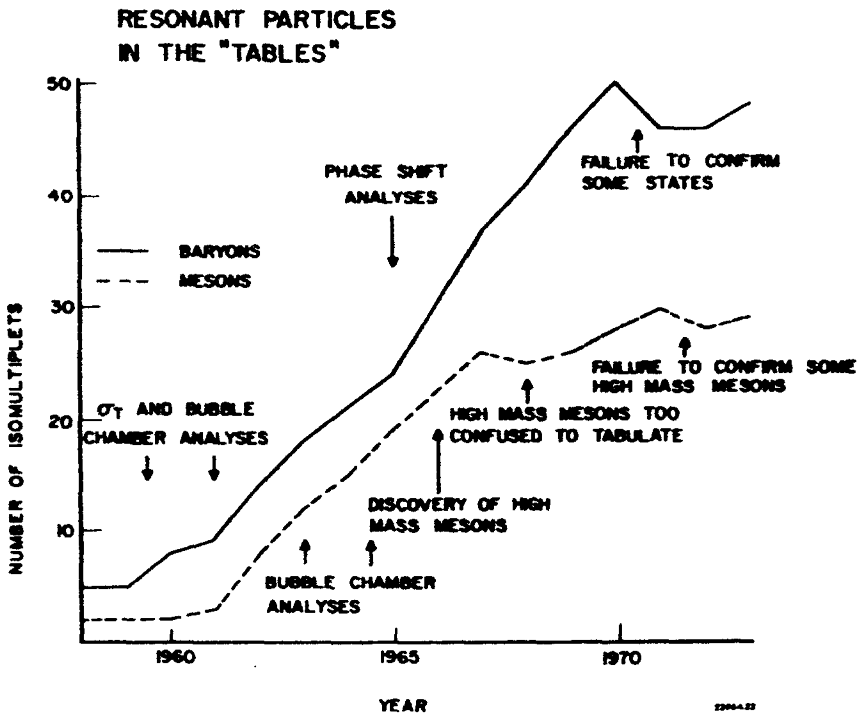

100
10
$(d\sigma/d\Omega)_{180°}$ (μb/sr)
Δ(2420)
Δ(2850)
2.0
2.5
3.0
3.5
4.0
4.5
M (π^+p) GeV

Fig. 8



$\pi^- p \to n\pi^0$
$\frac{d\sigma}{d\Omega}(0°)$
= This Experiment
= Borgeaud (1964)
= Crouch (1968)
0.8
0.6
0.4
0.2
0.0
1.0
1.5
2.0
2.5
$d\sigma/d\Omega\,(0°)$ - (mb/sr)
p_{π^-} - (GeV/c)

Fig. 9



RESONANT PARTICLES
IN THE "TABLES"
50
40
30
20
10
BARYONS
MESONS
PHASE SHIFT
ANALYSES
FAILURE TO CONFIRM
SOME STATES
FAILURE TO CONFIRM SOME
HIGH MASS MESONS
HIGH MASS MESONS TOO
CONFUSED TO TABULATE
σ_T AND BUBBLE
CHAMBER ANALYSES
DISCOVERY OF HIGH
MASS MESONS
BUBBLE CHAMBER
ANALYSES
NUMBER OF ISOMULTIPLETS
1960
1965
1970
YEAR

Fig. 10

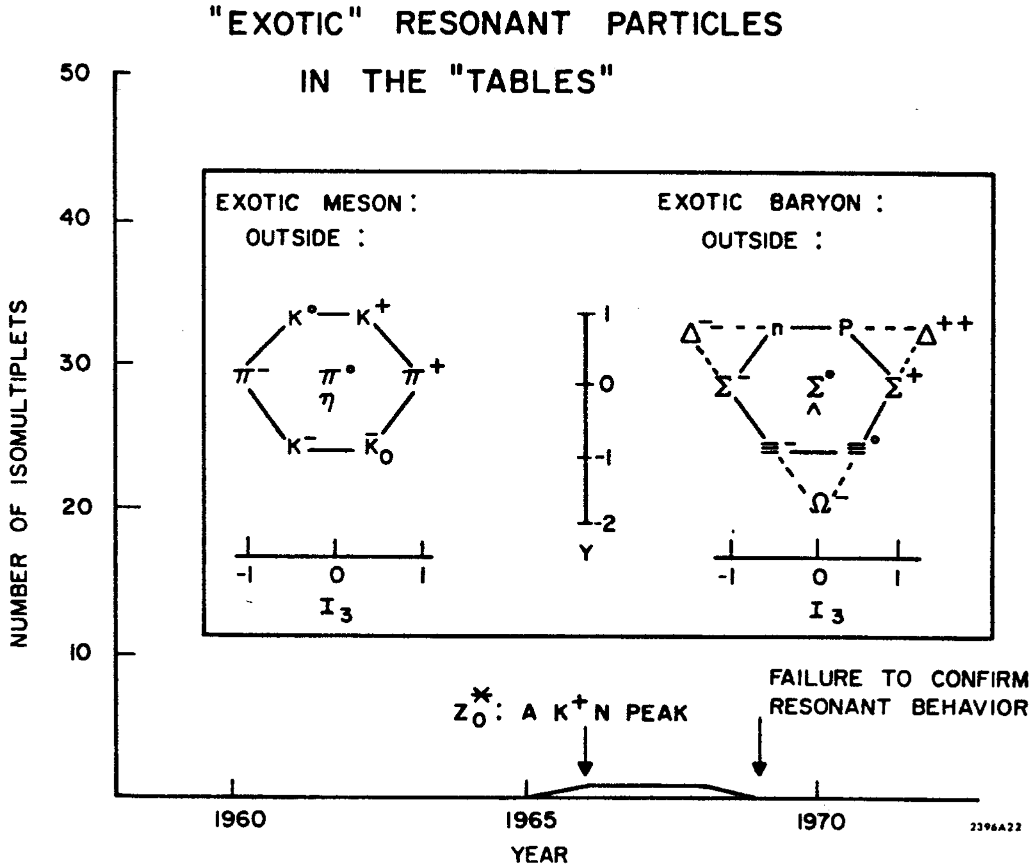

"EXOTIC" RESONANT PARTICLES
IN THE "TABLES"
NUMBER OF ISOMULTIPLETS
EXOTIC MESON:
OUTSIDE :
EXOTIC BARYON :
OUTSIDE :
Y
I_3
Z_0^*: A K^+N PEAK
FAILURE TO CONFIRM
RESONANT BEHAVIOR
1960
1965
1970
YEAR
2396A22

Fig. 11

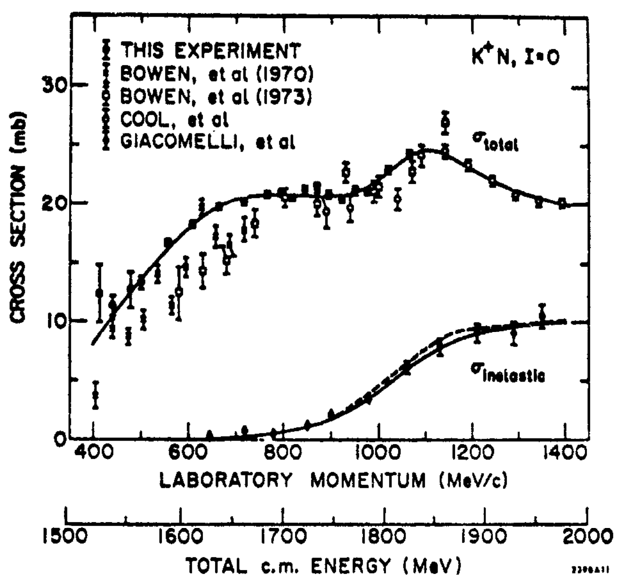

THIS EXPERIMENT
BOWEN, et al (1970)
BOWEN, et al (1973)
COOL, et al
GIACOMELLI, et al
K^+N, $I=0$
σ_{total}
$\sigma_{inelastic}$
CROSS SECTION (mb)
LABORATORY MOMENTUM (MeV/c)
TOTAL c.m. ENERGY (MeV)

Fig. 12

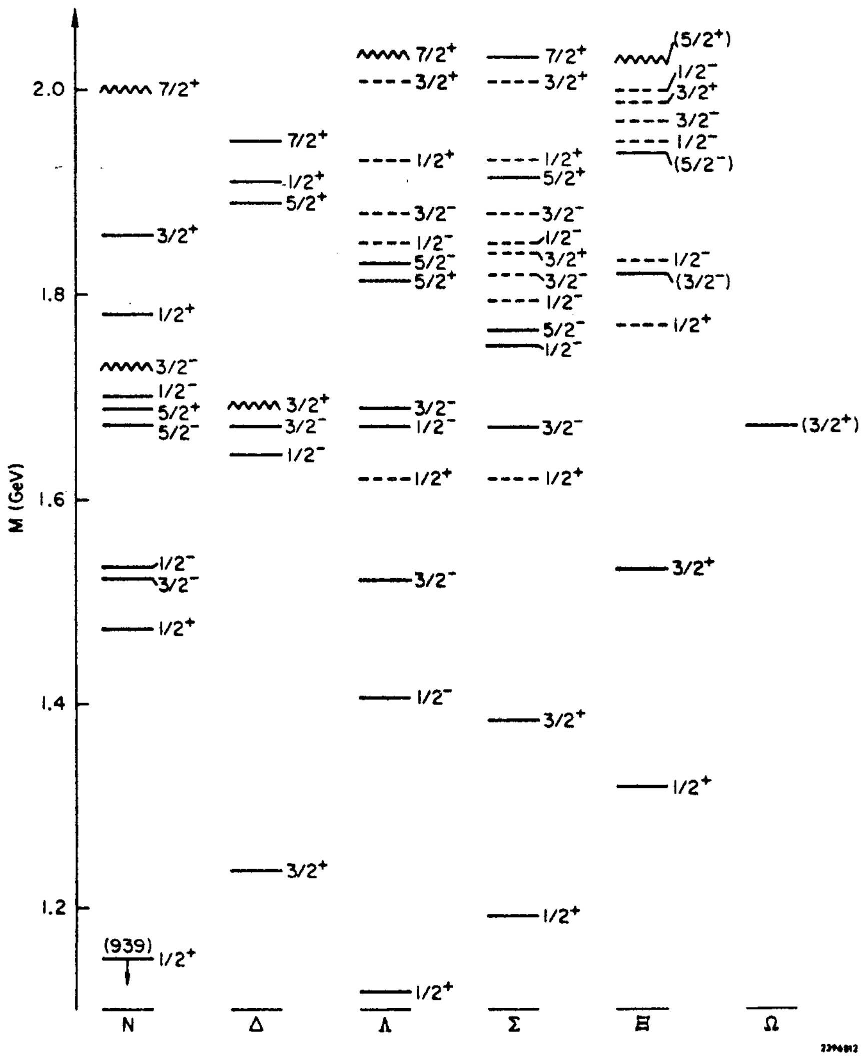


Fig. 13

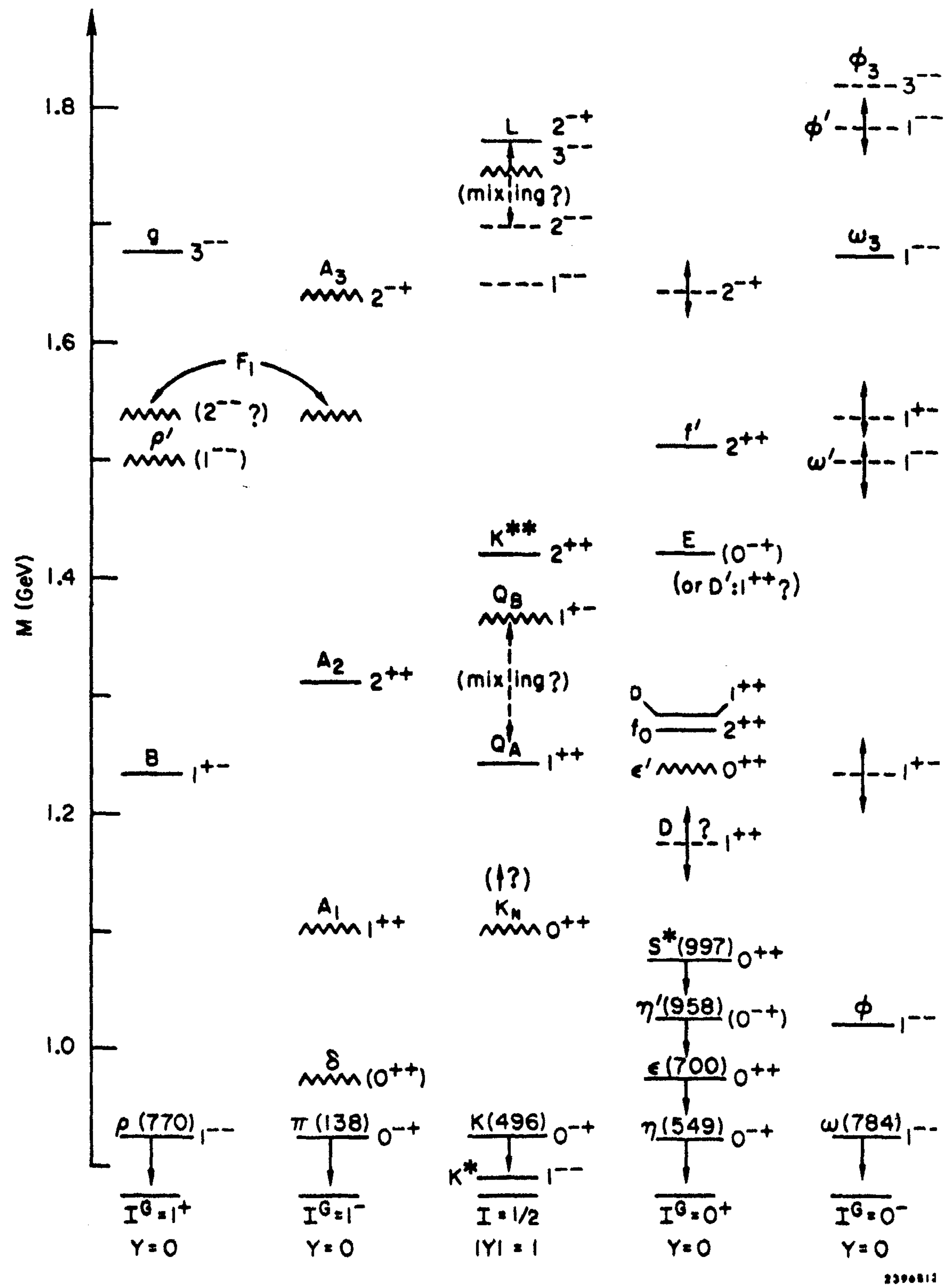
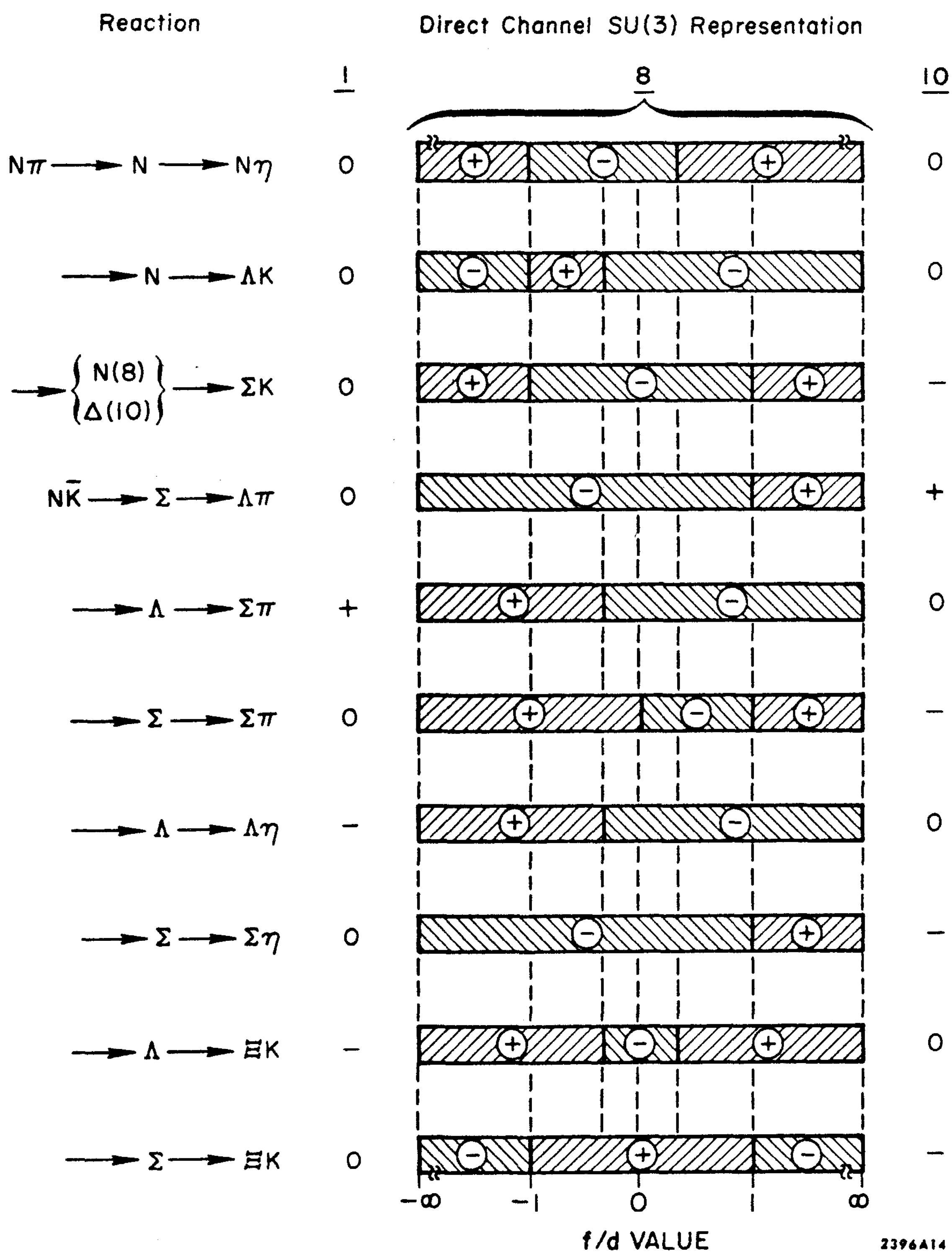

M (GeV)
1.8
1.6
1.4
1.2
1.0
g 3⁻⁻
B 1⁺⁻
F₁
(2⁻⁻ ?)
ρ′ (1⁻⁻)
ρ (770) 1⁻⁻
A₃ 2⁻⁺
A₂ 2⁺⁺
A₁ 1⁺⁺
δ (0⁺⁺)
π (138) 0⁻⁺
L 2⁻⁺
3⁻⁻
(mixing?)
2⁻⁻
1⁻⁻
K** 2⁺⁺
Q_B 1⁺⁻
(mixing?)
Q_A 1⁺⁺
(↕?)
K_N 0⁺⁺
K(496) 0⁻⁺
K* 1⁻⁻
2⁻⁺
f′ 2⁺⁺
E (0⁻⁺)
(or D′:1⁺⁺?)
D 1⁺⁺
f₀ 2⁺⁺
ε′ 0⁺⁺
D ? 1⁺⁺
S*(997) 0⁺⁺
η′(958) (0⁻⁺)
ε(700) 0⁺⁺
η(549) 0⁻⁺
φ₃ 3⁻⁻
φ′ 1⁻⁻
ω₃ 1⁻⁻
1⁺⁻
ω′ 1⁻⁻
1⁺⁻
φ 1⁻⁻
ω(784) 1⁻⁻
I^G=1⁺ Y=0
I^G=1⁻ Y=0
I=1/2 |Y|=1
I^G=0⁺ Y=0
I^G=0⁻ Y=0

Fig. 14



Reaction
Direct Channel SU(3) Representation
1
8
10
Nπ → N → Nη
→ N → ΛK
→ {N(8) / Δ(10)} → ΣK
NK̄ → Σ → Λπ
→ Λ → Σπ
→ Σ → Σπ
→ Λ → Λη
→ Σ → Ση
→ Λ → ΞK
→ Σ → ΞK
−∞
−1
0
∞
f/d VALUE
2396A14

Fig. 15

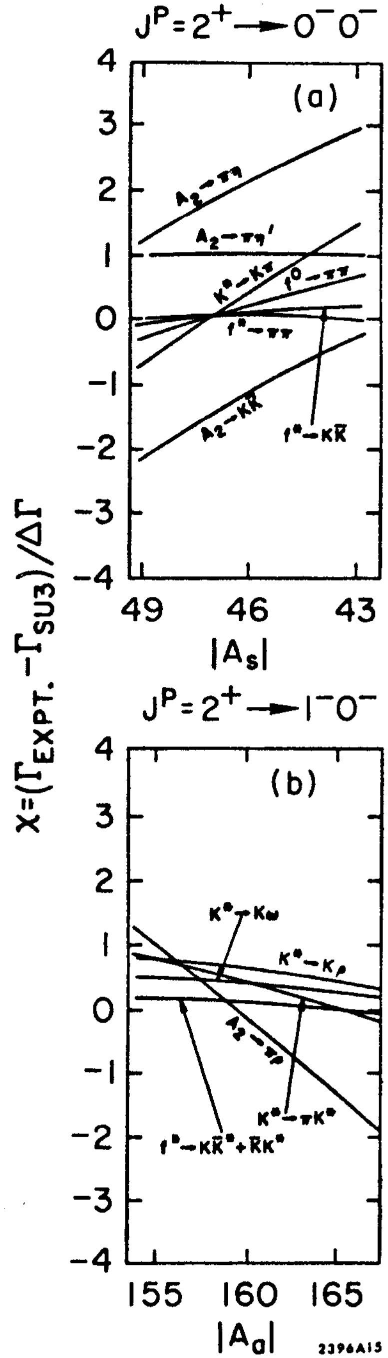


Fig. 16

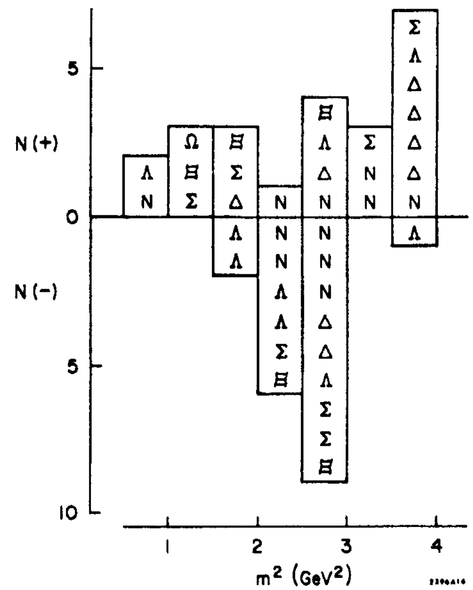


Fig. 17

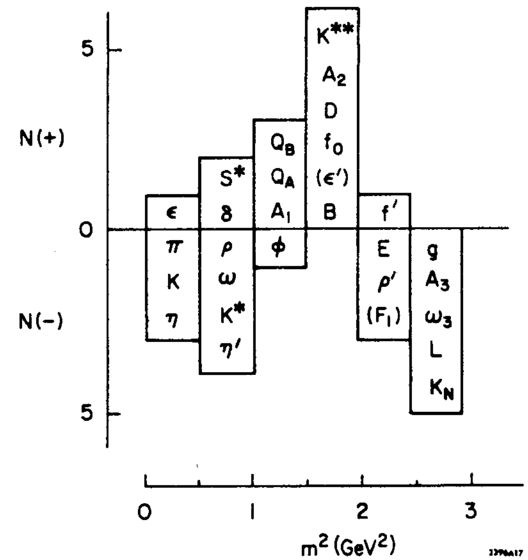


Fig. 18

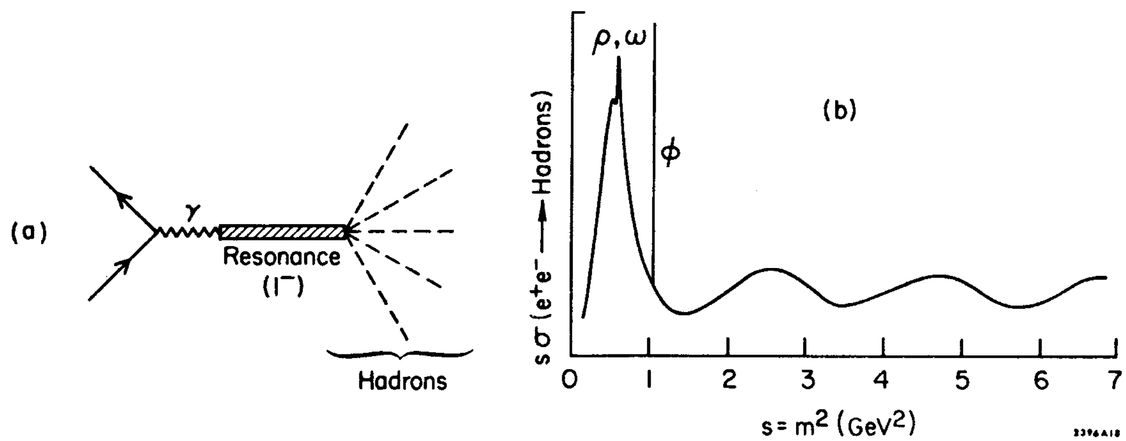
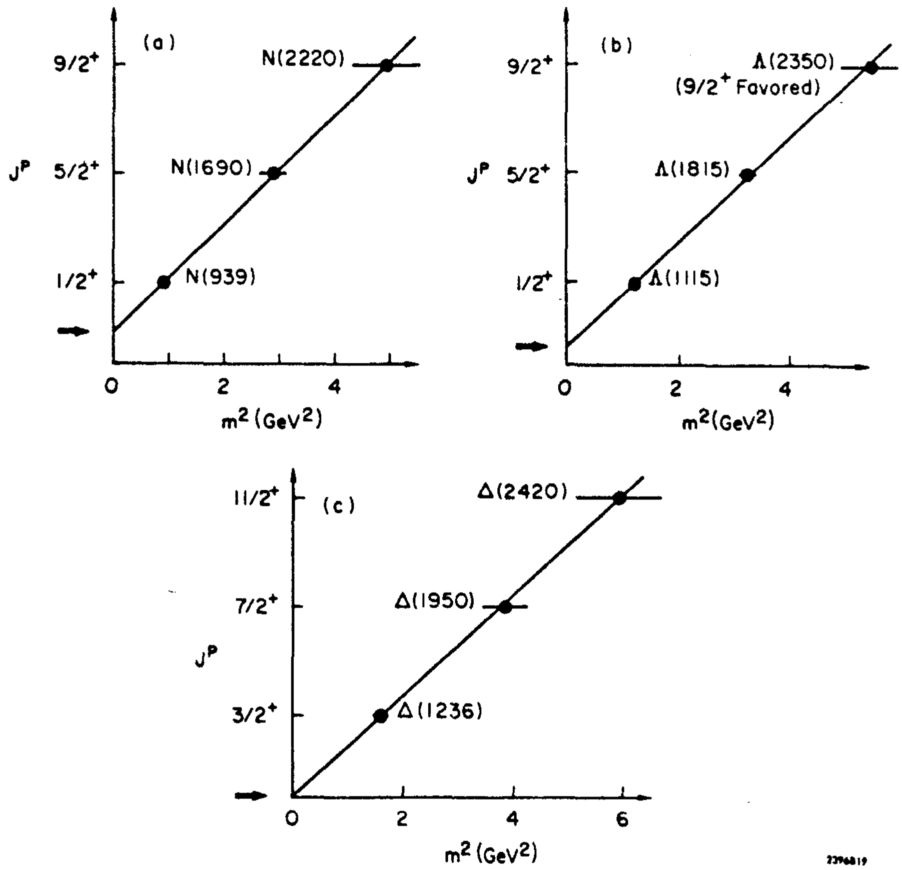
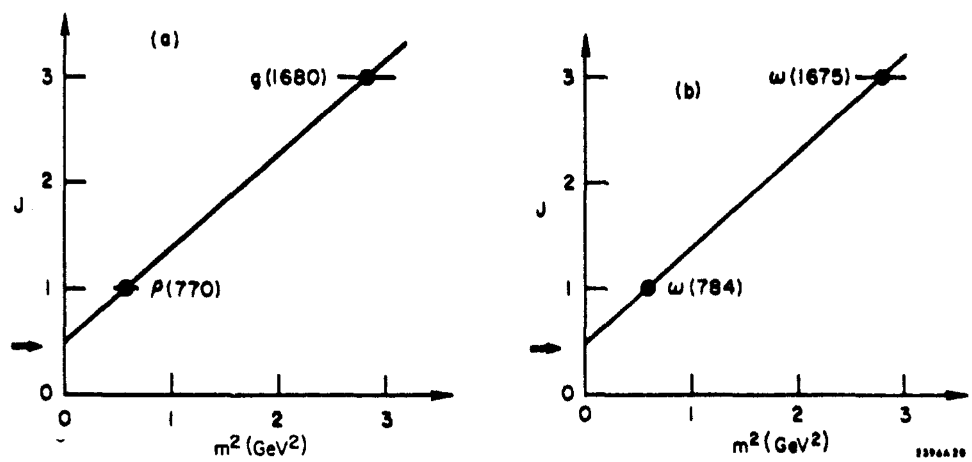


Fig. 19



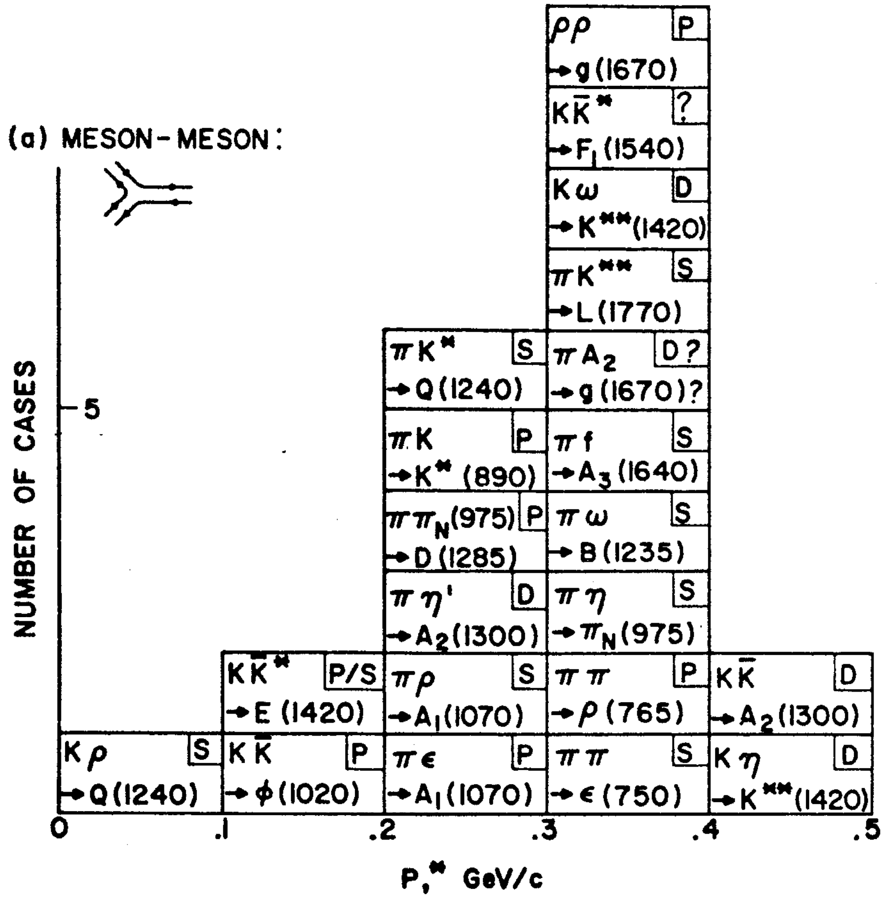
(a)
(b)
(c)
N(2220)
N(1690)
N(939)
Λ(2350)
(9/2+ Favored)
Λ(1815)
Λ(1115)
Δ(2420)
Δ(1950)
Δ(1236)
J^P
9/2+
5/2+
1/2+
11/2+
7/2+
3/2+
0
2
4
6
m^2 (GeV^2)

Fig. 20

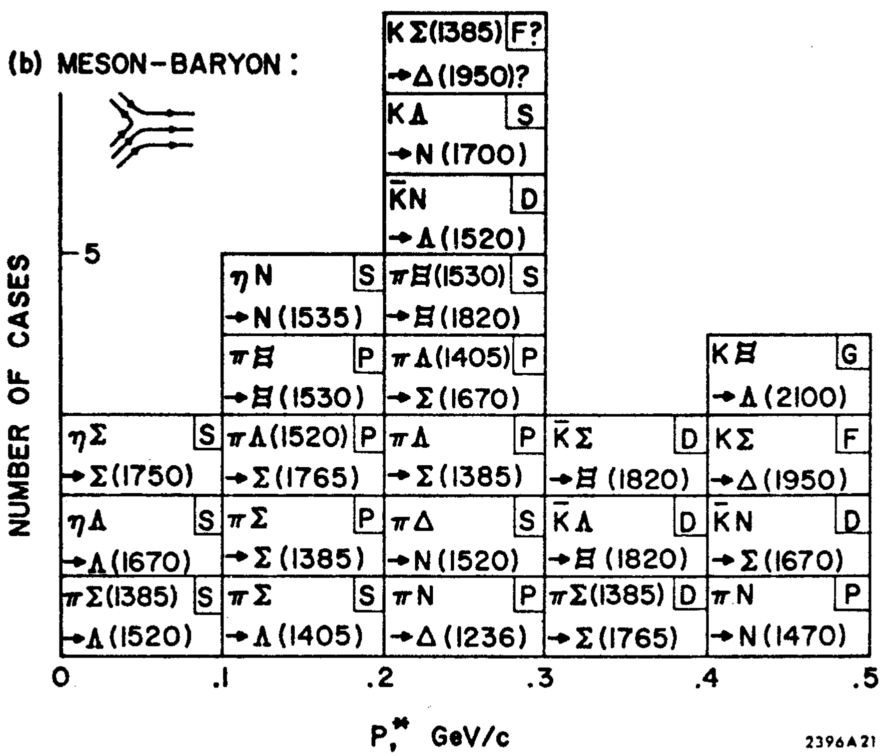


(a)
(b)
g(1680)
ρ(770)
ω(1675)
ω(784)
J
0
1
2
3
m^2 (GeV^2)

Fig. 21

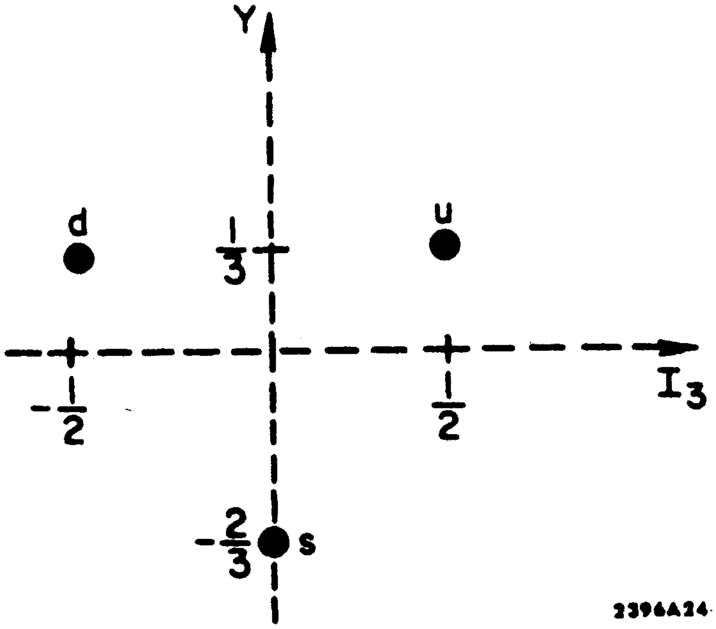


(a) MESON-MESON:
NUMBER OF CASES
5
0
.1
.2
.3
.4
.5
P,* GeV/c
Kρ S
→Q(1240)
KK̄ P
→φ(1020)
KK̄* P/S
→E (1420)
πε P
→A₁(1070)
πρ S
→A₁(1070)
πη' D
→A₂(1300)
ππ_N(975) P
→D (1285)
πK P
→K* (890)
πK* S
→Q(1240)
ππ S
→ε (750)
ππ P
→ρ (765)
πη S
→π_N(975)
πω S
→B(1235)
πf S
→A₃(1640)
πA₂ D?
→g (1670)?
πK** S
→L(1770)
Kω D
→K**(1420)
KK̄* ?
→F₁(1540)
ρρ P
→g(1670)
Kη D
→K**(1420)
KK̄ D
→A₂(1300)



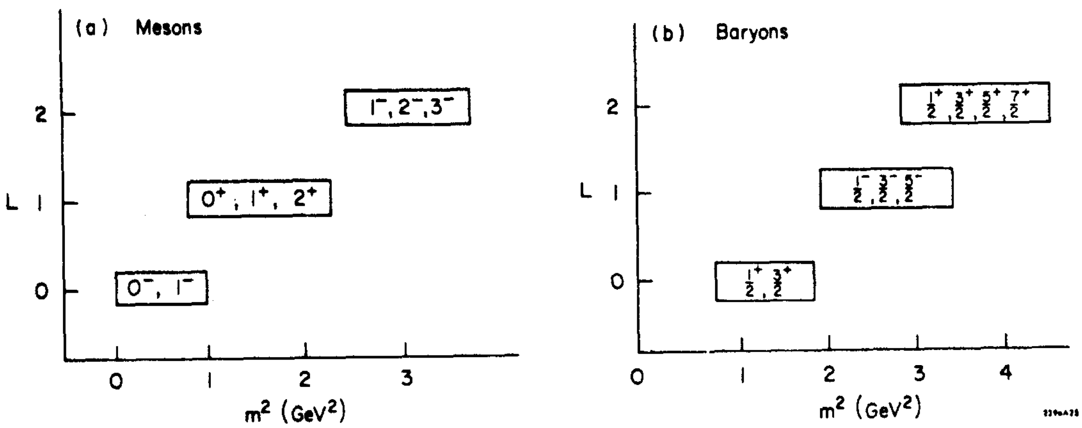
(b) MESON-BARYON:
NUMBER OF CASES
5
0
.1
.2
.3
.4
.5
P,* GeV/c
πΣ(1385) S
→Λ(1520)
ηΛ S
→Λ(1670)
ηΣ S
→Σ(1750)
πΣ S
→Λ(1405)
πΣ P
→Σ(1385)
πΛ(1520) P
→Σ(1765)
πΞ P
→Ξ(1530)
ηN S
→N(1535)
πN P
→Δ(1236)
πΔ S
→N(1520)
πΛ P
→Σ(1385)
πΛ(1405) P
→Σ(1670)
πΞ(1530) S
→Ξ(1820)
K̄N D
→Λ(1520)
KΛ S
→N(1700)
KΣ(1385) F?
→Δ(1950)?
πΣ(1385) D
→Σ(1765)
K̄Λ D
→Ξ(1820)
K̄Σ D
→Ξ(1820)
πN P
→N(1470)
K̄N D
→Σ(1670)
KΣ F
→Δ(1950)
KΞ G
→Λ(2100)
2396A21

Fig. 22



Y
d
u
$\frac{1}{3}$
$-\frac{1}{2}$
$\frac{1}{2}$
I_3
$-\frac{2}{3}$
s
2396A24

Fig. 23



(a) Mesons
L
$0^-, 1^-$
$0^+; 1^+, 2^+$
$1^-, 2^-, 3^-$
m^2 (GeV^2)
(b) Baryons
$\frac{1}{2}^+, \frac{3}{2}^+$
$\frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-$
$\frac{1}{2}^+, \frac{3}{2}^+, \frac{5}{2}^+, \frac{7}{2}^+$
m^2 (GeV^2)

Fig. 24

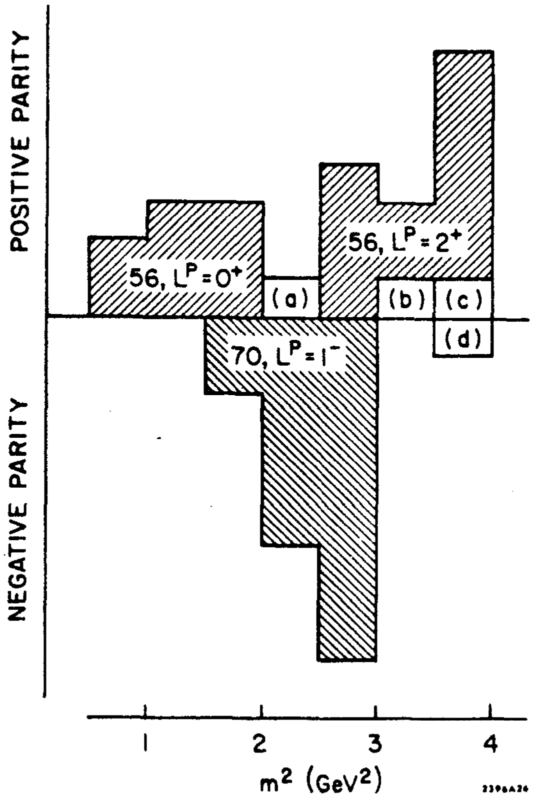

POSITIVE PARITY
NEGATIVE PARITY
56, $L^P = 0^+$
56, $L^P = 2^+$
70, $L^P = 1^-$
(a)
(b)
(c)
(d)
1
2
3
4
m^2 (GeV^2)

Fig. 25

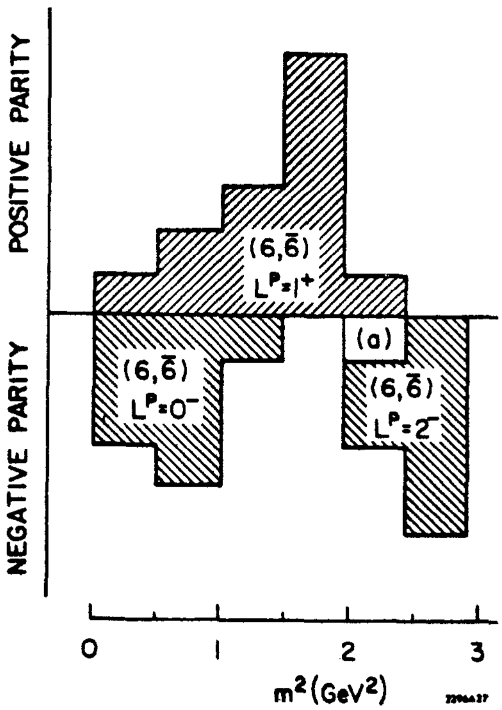

POSITIVE PARITY
NEGATIVE PARITY
$(6,\bar{6})$ $L^P = 1^+$
$(6,\bar{6})$ $L^P = 0^-$
$(6,\bar{6})$ $L^P = 2^-$
(a)
0
1
2
3
m^2(GeV^2)

Fig. 26

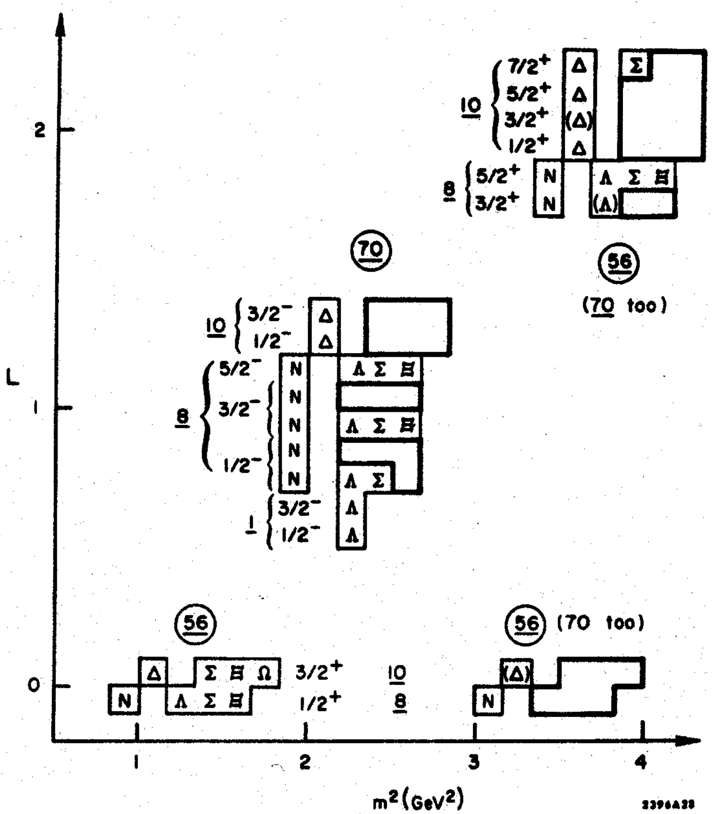


Fig. 27

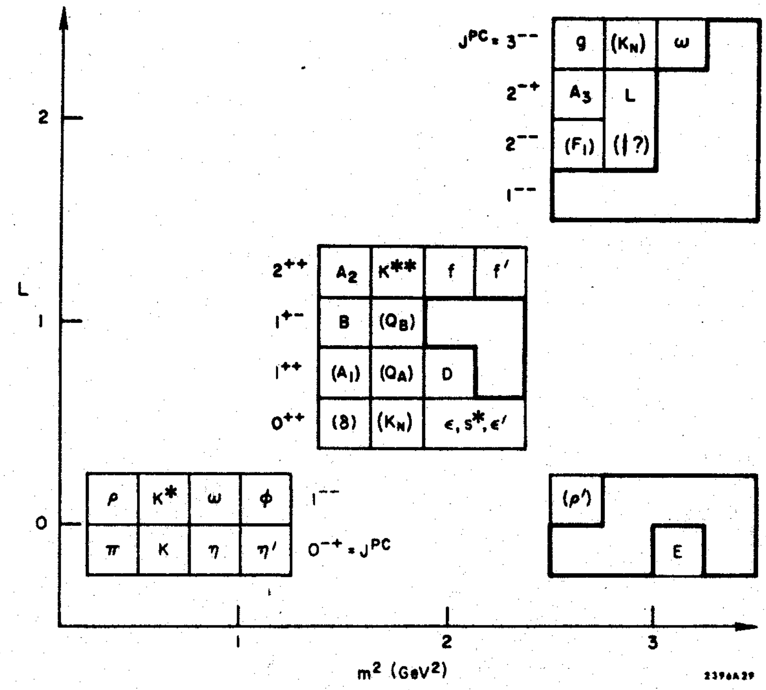


Fig. 28

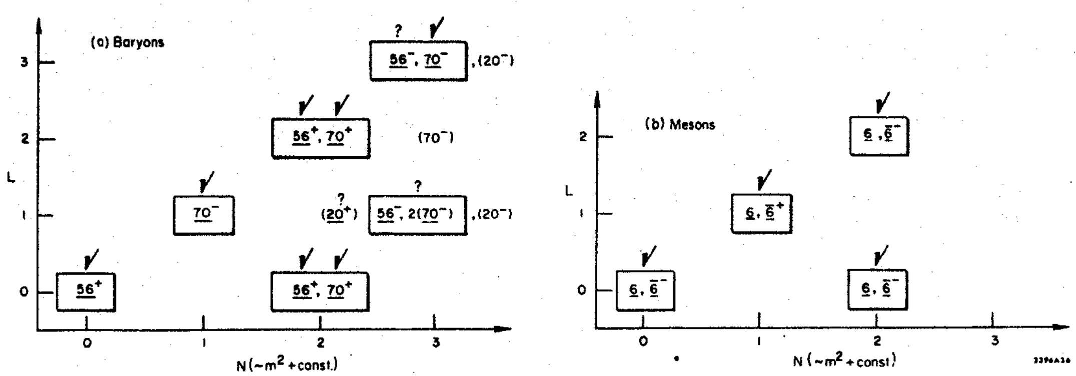


Fig. 29

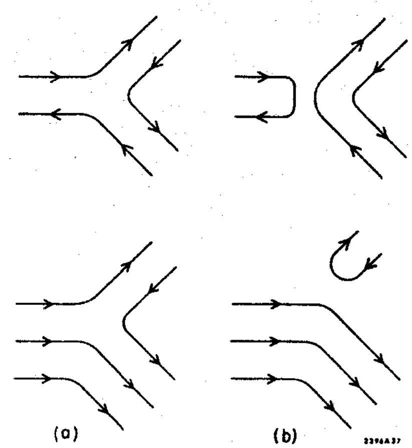


Fig. 30

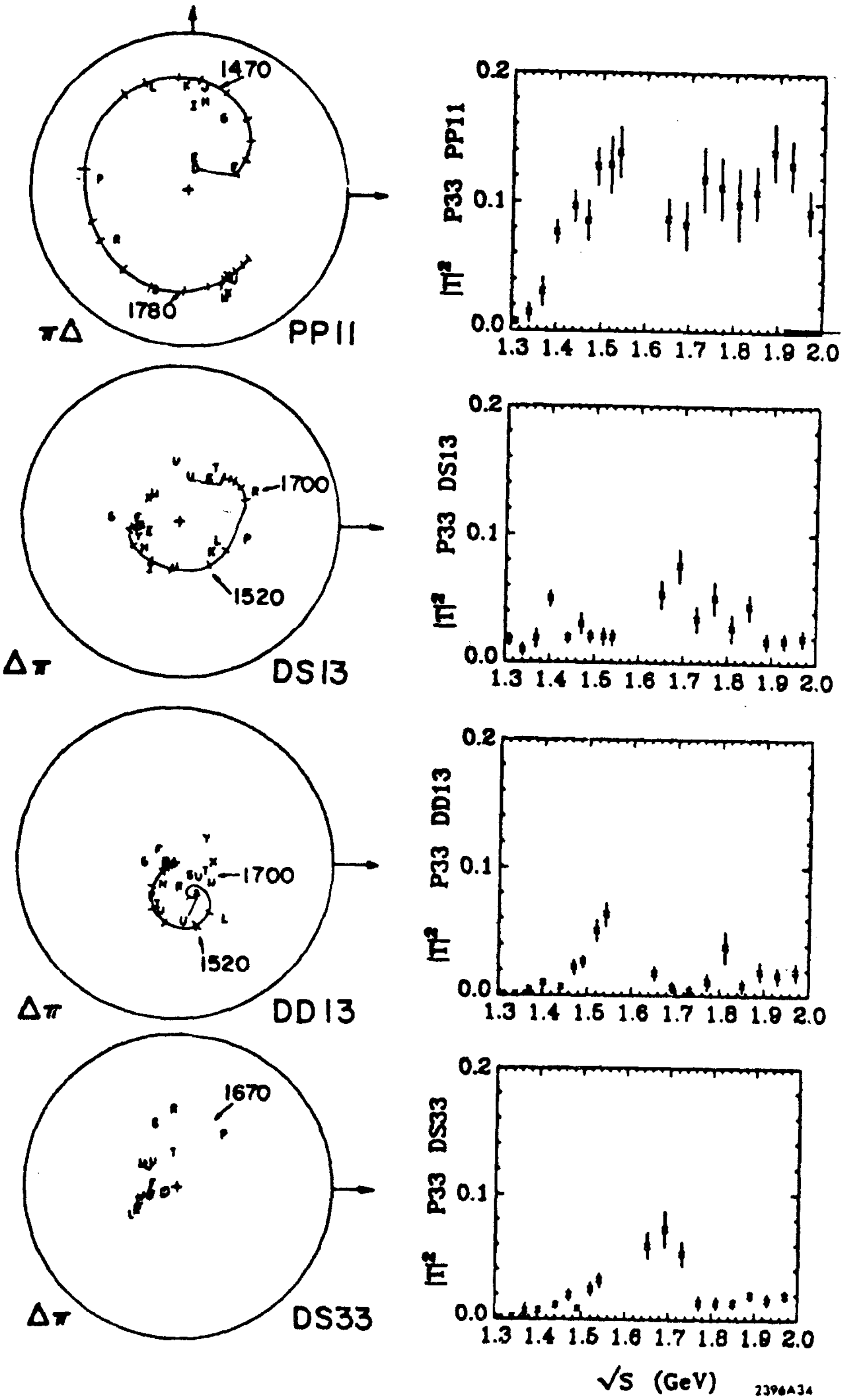
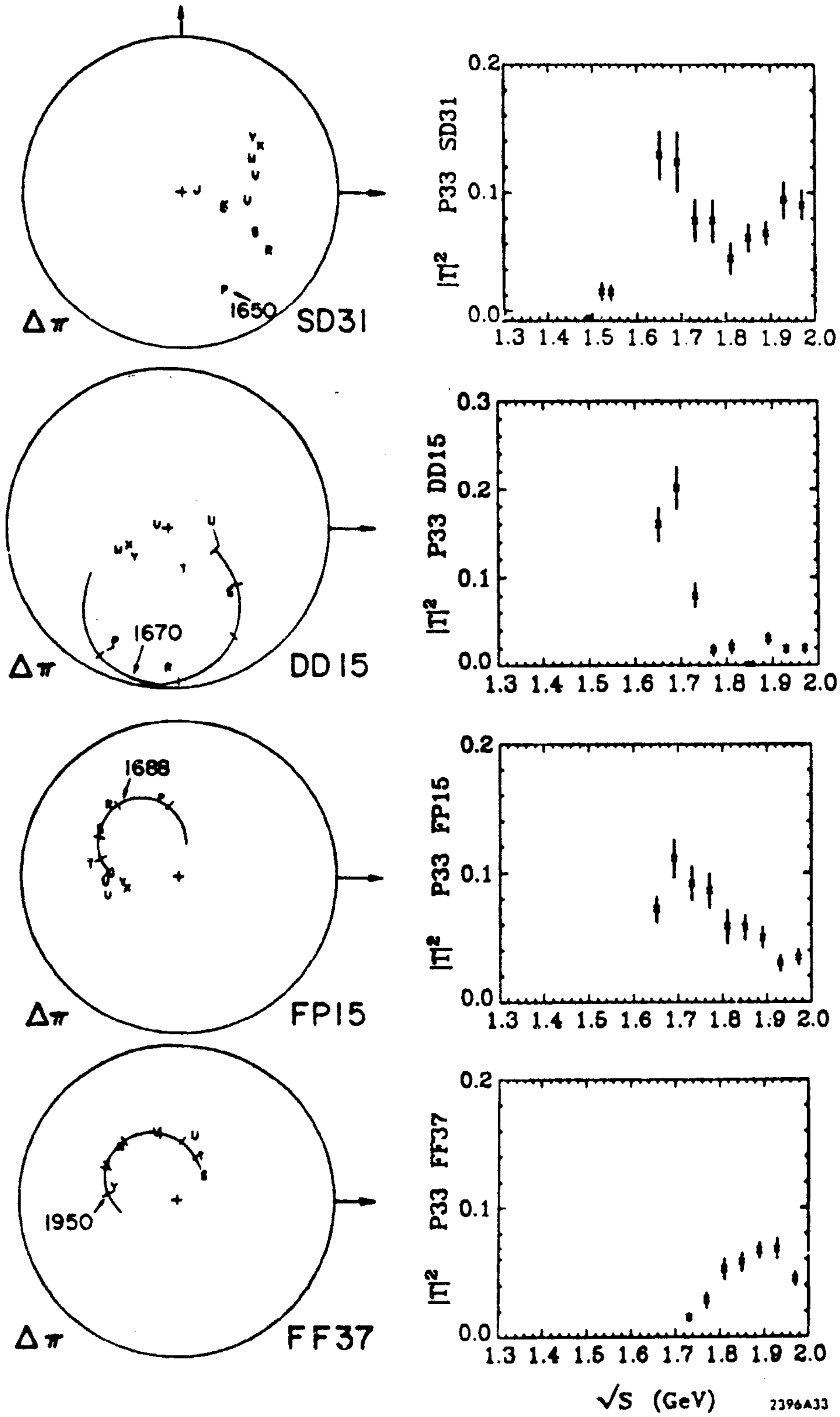

1470
1780
πΔ
PP11
0.2
0.1
0.0
$|T|^2$ P33 PP11
1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0
1700
1520
Δπ
DS13
$|T|^2$ P33 DS13
1700
1520
Δπ
DD13
$|T|^2$ P33 DD13
1670
Δπ
DS33
$|T|^2$ P33 DS33
√s (GeV)
2396A34

Fig. 31a



1650
Δπ
SD31
1670
DD15
1688
FP15
1950
FF37
0.2
0.1
0.0
0.3
|T|² P33 SD31
|T|² P33 DD15
|T|² P33 FP15
|T|² P33 FF37
1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0
√s (GeV)
2396A33

Fig. 31b

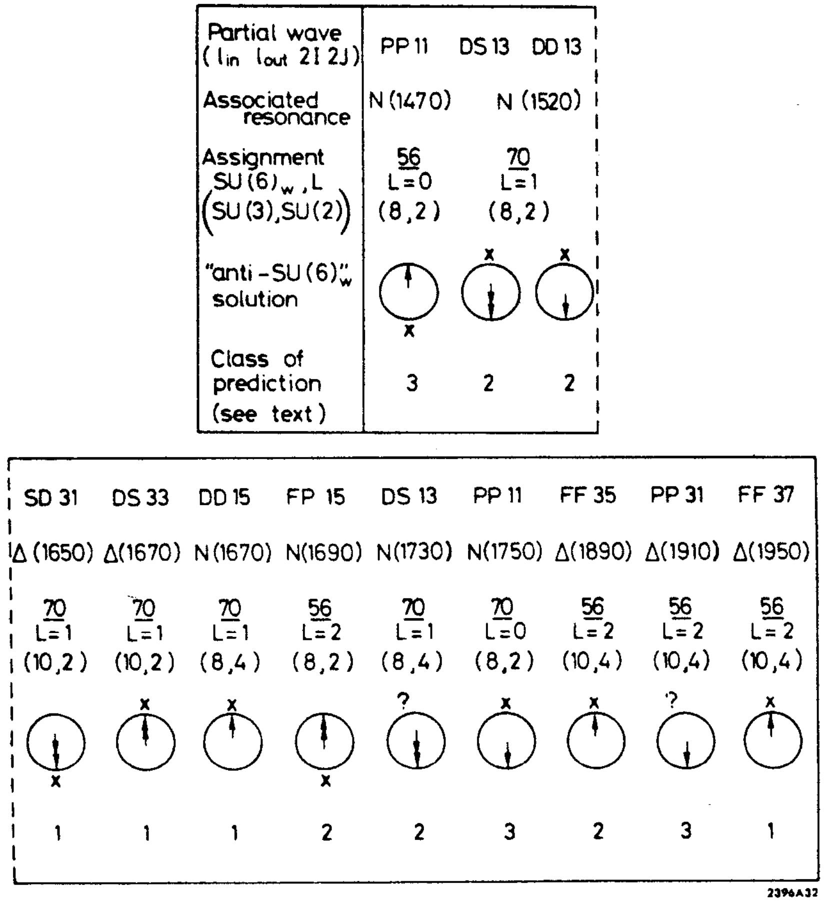


Fig. 32a

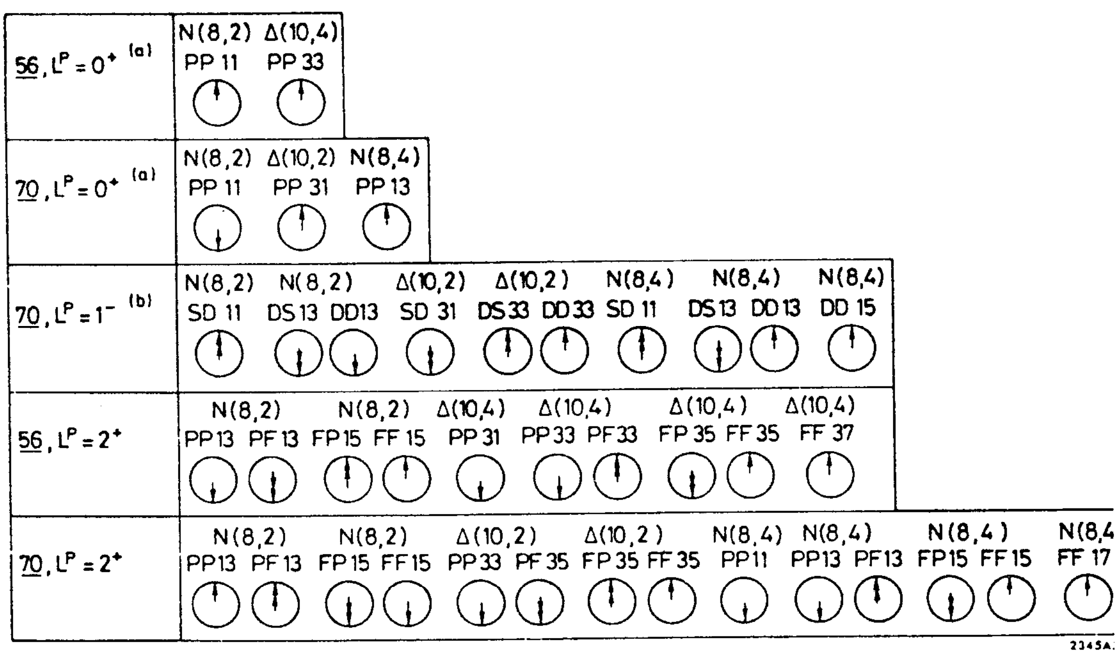
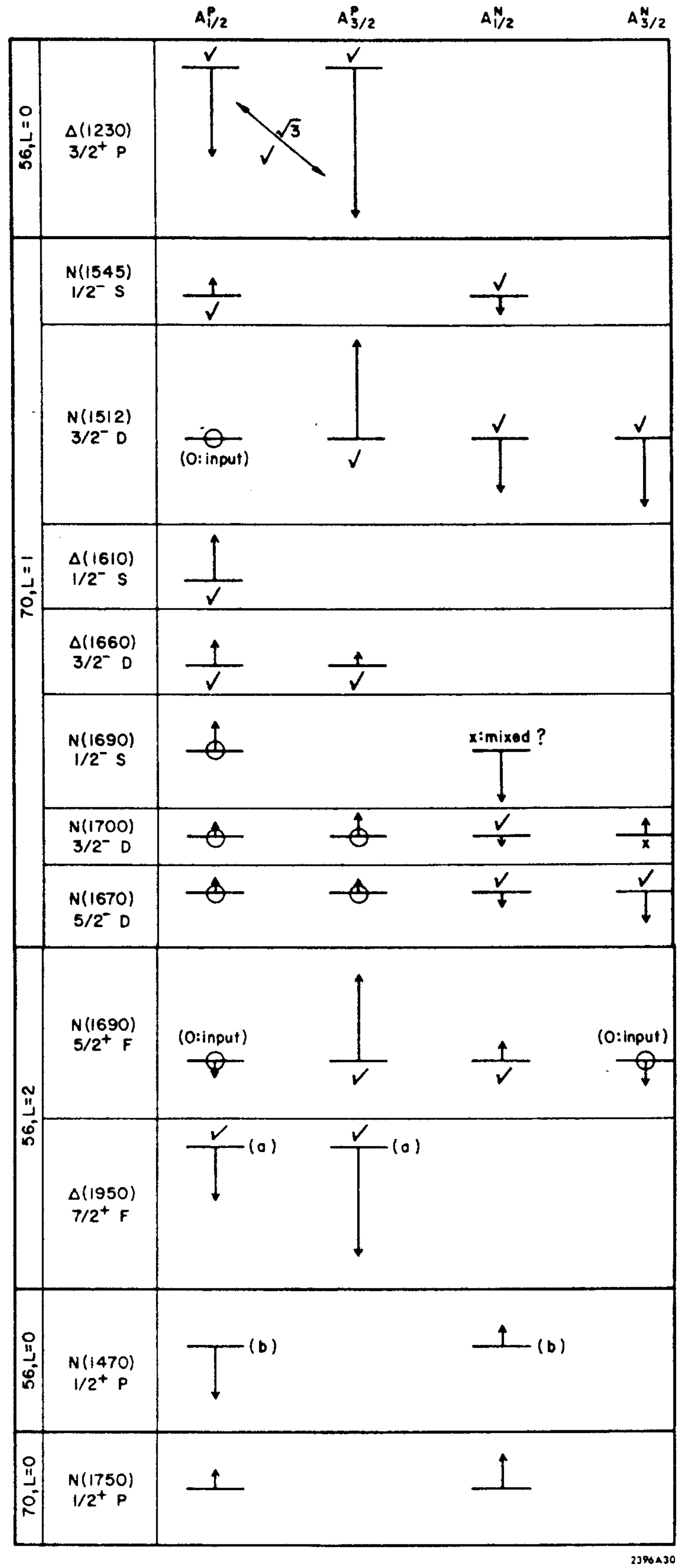


Fig. 32b



$A^P_{1/2}$
$A^P_{3/2}$
$A^N_{1/2}$
$A^N_{3/2}$
56,L=0
Δ(1230)
3/2⁺ P
$\sqrt{3}$
70,L=1
N(1545)
1/2⁻ S
N(1512)
3/2⁻ D
(O: input)
Δ(1610)
1/2⁻ S
Δ(1660)
3/2⁻ D
N(1690)
1/2⁻ S
x: mixed ?
N(1700)
3/2⁻ D
N(1670)
5/2⁻ D
56,L=2
N(1690)
5/2⁺ F
(O: input)
(O: input)
Δ(1950)
7/2⁺ F
(a)
(a)
56,L=0
N(1470)
1/2⁺ P
(b)
(b)
70,L=0
N(1750)
1/2⁺ P
2396A30

Fig. 33

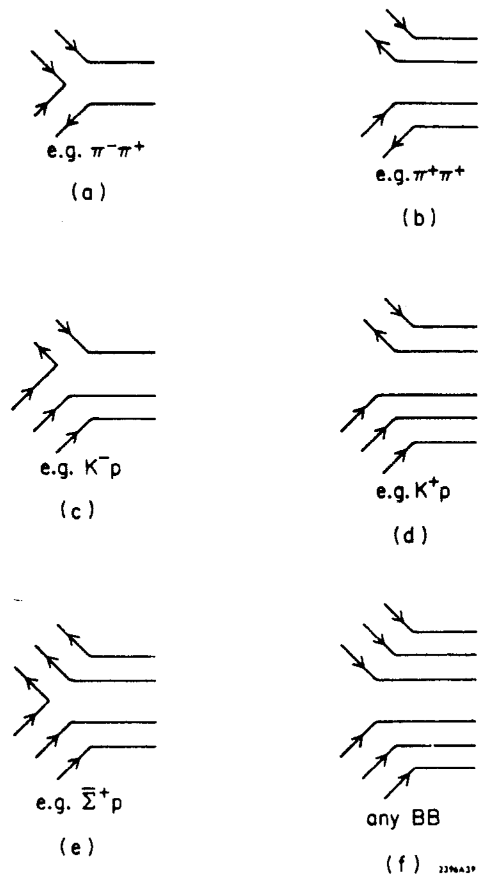

e.g. $\pi^-\pi^+$
(a)
e.g. $\pi^+\pi^+$
(b)
e.g. K^-p
(c)
e.g. K^+p
(d)
e.g. $\bar{\Sigma}^+p$
(e)
any BB
(f)

Fig. 34

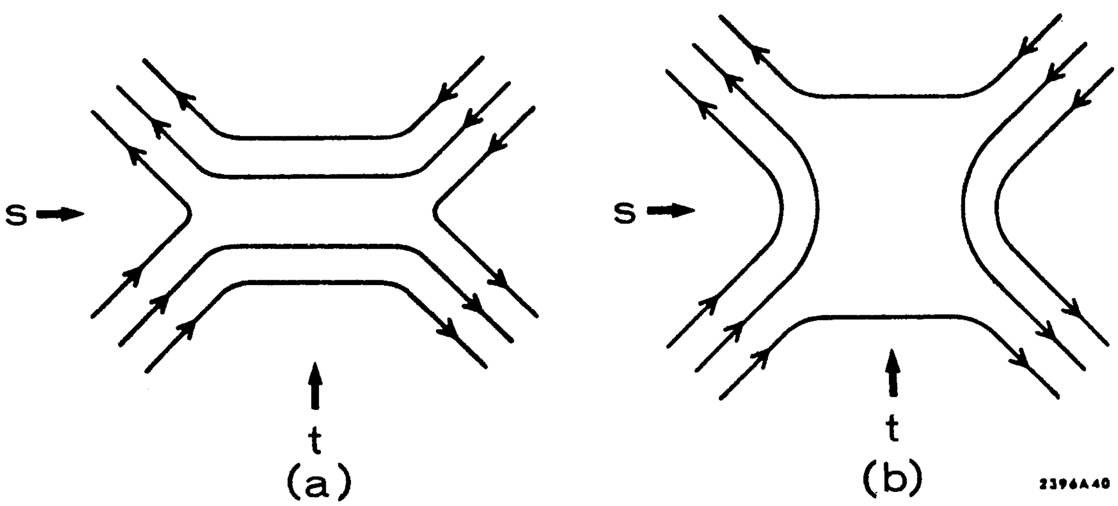
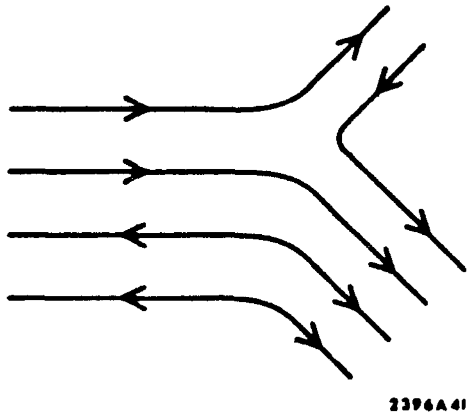
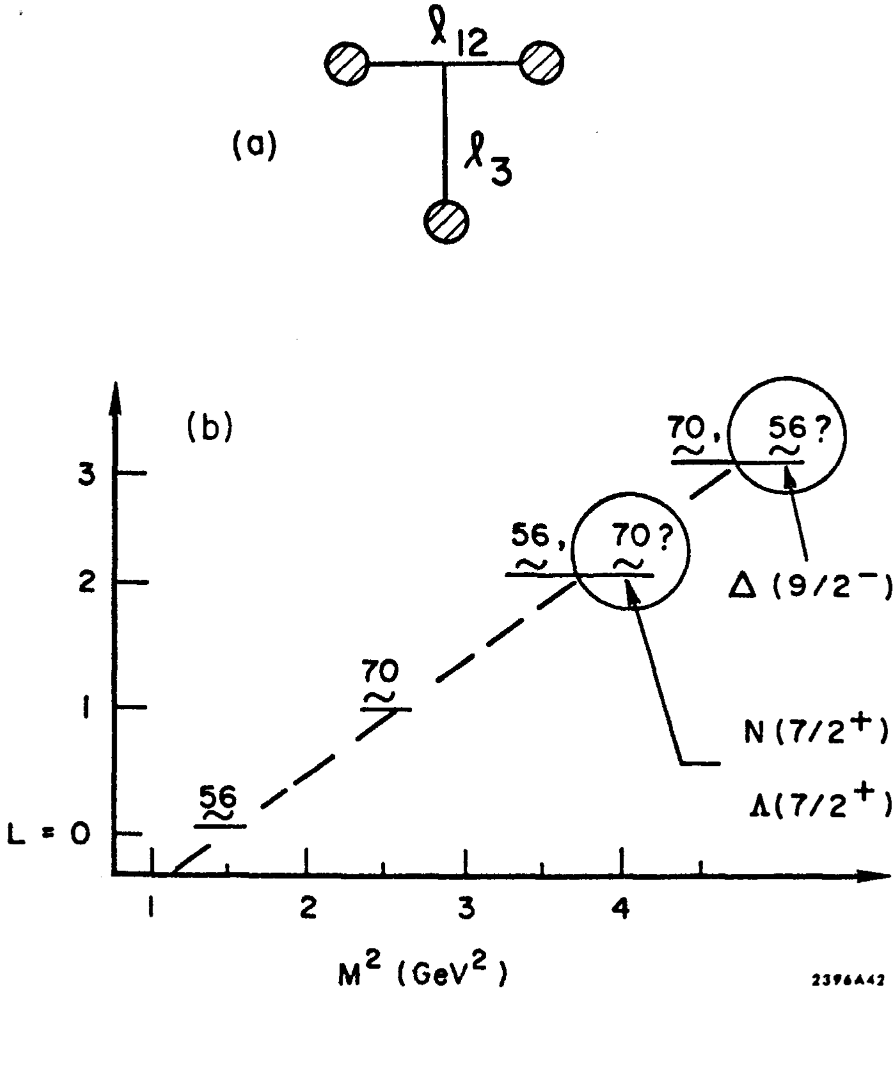

s
t
(a)
s
t
(b)
2396A40

Fig. 35



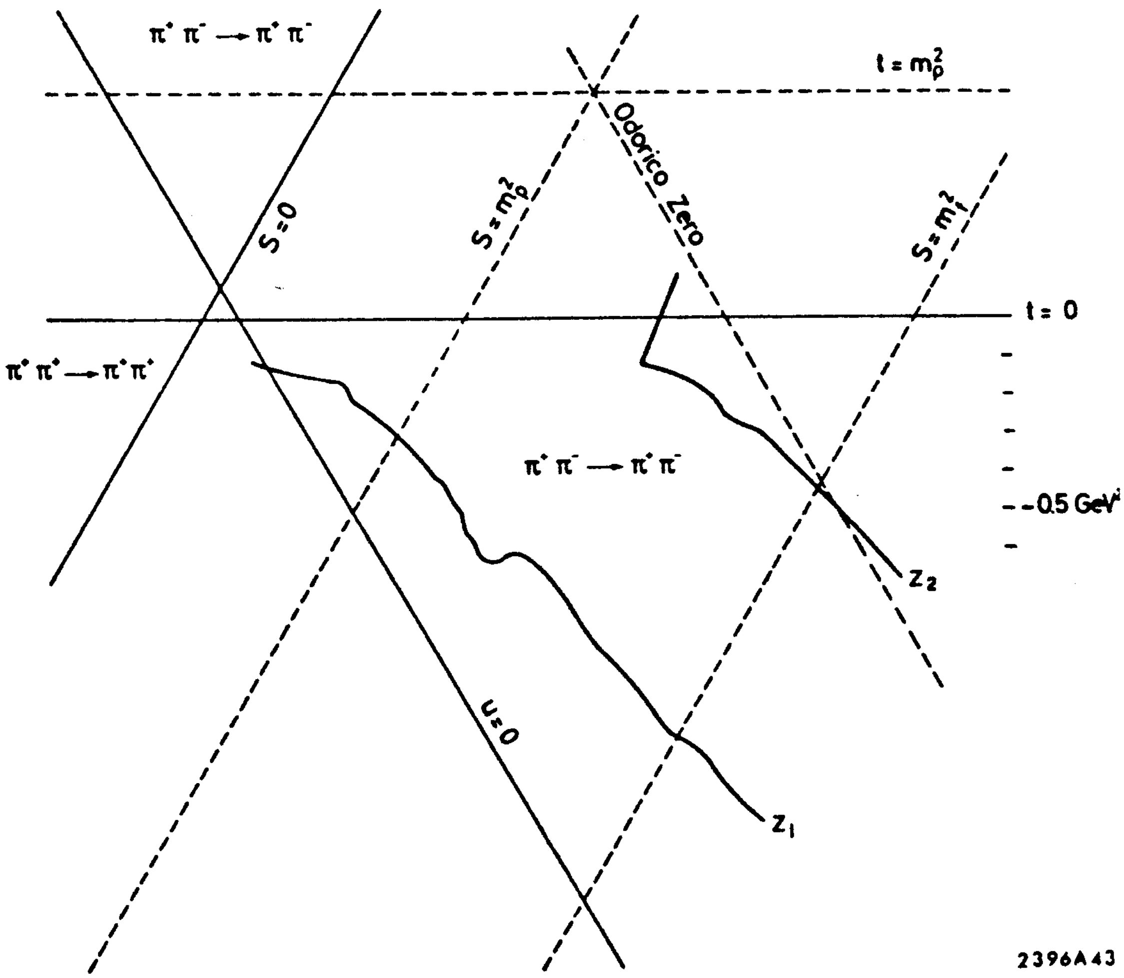
2396A41

Fig 36



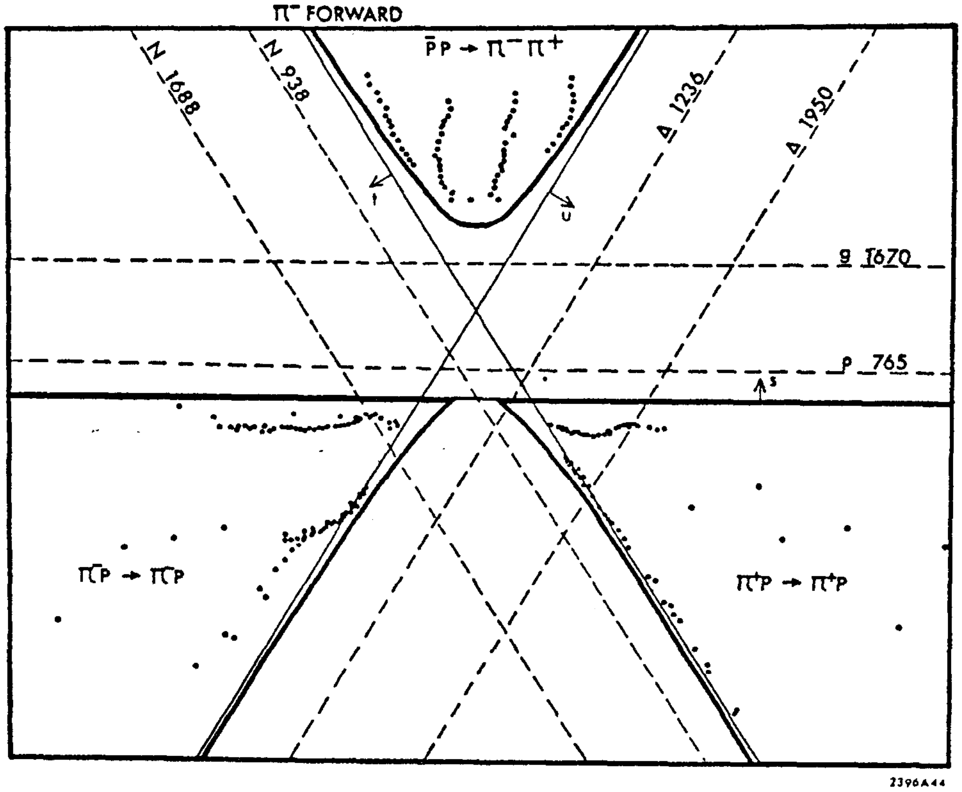
(a)
ℓ_{12}
ℓ_3
(b)
L = 0
1
2
3
56
70
56, 70?
70, 56?
N (7/2+)
Λ(7/2+)
Δ (9/2−)
1
2
3
4
M2 (GeV2)
2396A42

Fig. 37



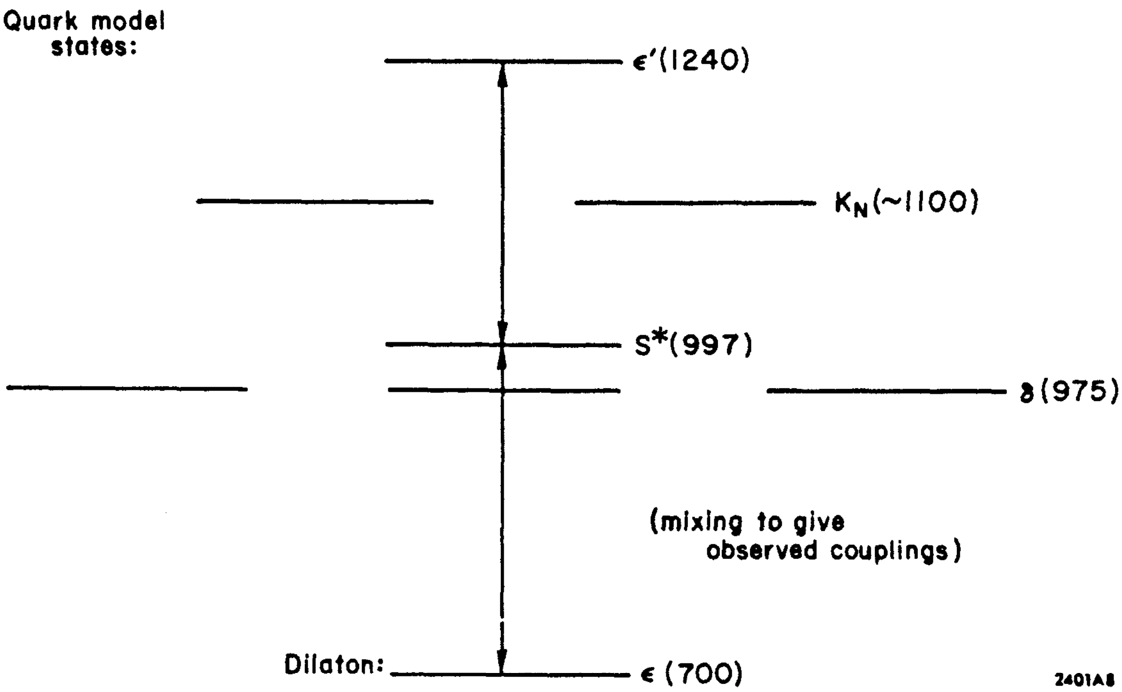
π⁺ π⁻ → π⁺ π⁻
t = m_ρ^2
S=0
S = m_ρ^2
Odorico Zero
S = m_f^2
t = 0
π⁺ π⁺ → π⁺ π⁺
π⁺ π⁻ → π⁺ π⁻
-0.5 GeV²
Z₂
u=0
Z₁
2396A43

Fig. 38



π⁻ FORWARD
p̄p → π⁻π⁺
N 1688
N 938
Δ 1236
Δ 1950
t
u
g 1670
ρ 765
s
π⁻p → π⁻p
π⁺p → π⁺p
2396A44

Fig. 39



Quark model states:
ϵ′(1240)
K_N(~1100)
S*(997)
δ(975)
(mixing to give observed couplings)
Dilaton:
ϵ (700)
2401A8

Fig. 40

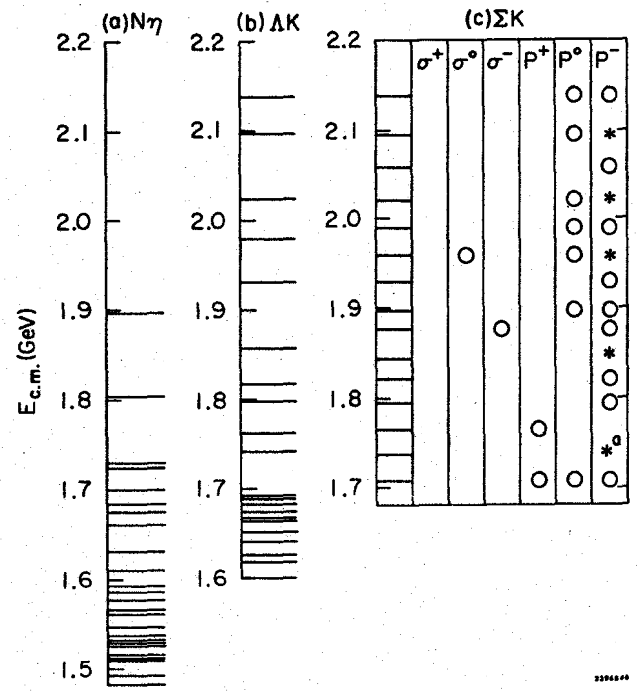


Fig. 41

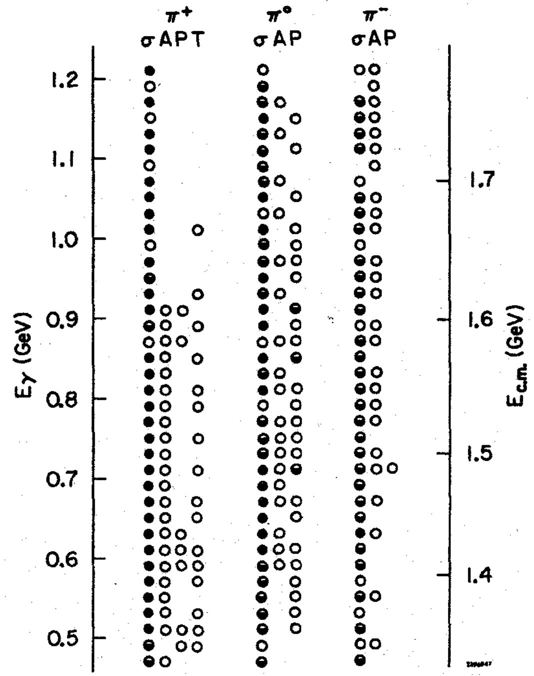


Fig. 42

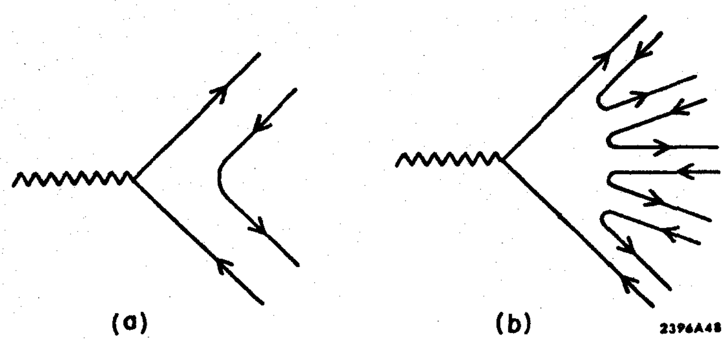


Fig. 43

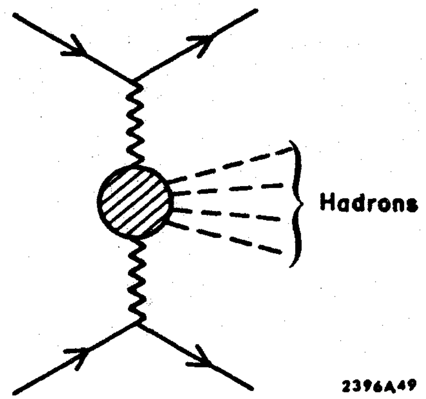


Fig. 44