MESON RESONANCES*

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Abstract

1) Several narrow resonances have been suggested in the 950 MeV region, but need confirmation.

2) The ambiguity in the I = 0,S-wave $\pi\pi$ phase shift above the ρ has been resolved in favor of the down solution. The phase changes rapidly near $K\bar{K}$ threshold, and the data are well fit with a pole at 980-37i MeV.

3) Little variation with mass has been found in the phase of the A_1 amplitude, suggesting that it is just kinematic enhancement. There could also be a resonance in this region, but even if it should exist, the mass and width are very uncertain.

4) All high statistics A_2 experiments are well fit by a single Breit-Wigner and the old CERN MMS data have been reanalyzed and found to be less significant than originally believed. It seems very likely that the A_2 is an ordinary resonance.

5) A clean high statistics sample of B(1235) $\rightarrow \pi\omega$ has been obtained and yields the expected $J^{PC} = 1^{+-}$.

6) Several experiments have found a new resonance, $\rho' \rightarrow \rho^0\pi^+\pi^-$ with $M \sim 1.5$ and $\Gamma \sim 0.4$ GeV.

7) None of the narrow high-mass objects reported previously have been confirmed in spite of considerable effort.

8) Still no exotic mesons.

*Work performed under the auspices of the U. S. Atomic Energy Commission

Introduction

The minirapporteurs provided an interesting and informative program at the parallel sessions; many of their talks are included in the proceedings and should be consulted for details.

Let me remind you that the Review of Particle Properties by the Particle Data Group (1971, 1972) contains more than just The Tables which we carry constantly with us. The data card listings in the back have not only lists of individual measurements, but also references and concise, well written discussions of current problems.

Much useful information was exchanged at the 1972 Philadelphia Conference on Experimental Meson Spectroscopy, and I thank Prof. A. Rosenfeld for supplying an advance copy of the proceedings. I would also like to thank the Scientific Secretaries, A. B. Wicklund and C. E. W. Ward, for their help.

$\pi\pi$ Scattering

Considerable work on $\pi\pi$ scattering has been carried out since the Kiev Conference two years ago. In particular, the sudden onset of inelasticity at $K\bar{K}$ threshold has been used to resolve the $I = 0$, S-wave ambiguity in the region above the ρ meson.

Since pion targets are unavailable, one must rely on the separation of one pion exchange (OPE) diagrams (Fig. 1) from the many other possible diagrams leading to dipion production. For experiments with sufficient statistics, this separation is made with a Chew-Low extrapolation to the pion pole. As has been emphasized (e.g., Kane 1970), these extrapolations are not without pitfalls. For example, one should avoid extrapolation of density matrix elements which have singularities between the physical region and the pion pole (Williams 1970). Another possible source of error comes from constraining the differential cross section for reactions such as $\pi^- p \to \pi^- \pi^+ n$ to go through zero at $t = 0$ as expected for simple OPE; absorption effects can displace this zero.

High statistics spark chamber data (Baillon 1971, Grayer 1972a) agree well with the Poor Man's Absorption model (Williams 1970; Froggatt and Morgan 1972 consider a generalization of this approach). Having once determined that a particular model reproduces the production

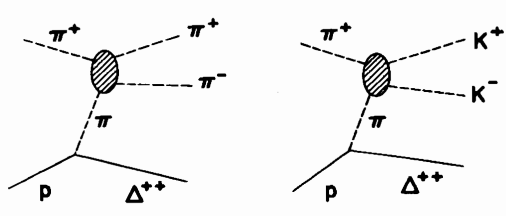

Fig. 1. Elastic and inelastic $\pi\pi$ scattering.

distributions, one can then use the model to investigate the validity of various extrapolation procedures. Williams (1972) finds that the higher order moments of the decay angular distribution do not extrapolate as simply as experimentalists have assumed. The situation is further complicated by the fact that other exchanges such as A_2 may be present, especially at larger t (Estabrooks and Martin 1972). In spite of all the complications, a reasonably consistent picture of $\pi\pi$ scattering has been obtained at various momenta from different reactions. See Peterson (1971) for a general review of the subject.

I = 0, S-Wave $\pi\pi$ Phase Shift

While the P-wave $\pi\pi$ phase shifts corresponding to the ρ meson have been known fairly well for many years, there has been considerable ambiguity in the I = 0, S-wave amplitude. Part of this ambiguity was removed a few years ago by careful extrapolation of the $\pi\pi$ cross section below the ρ mass. The ambiguity above the ρ has recently been resolved using the cusp effect at $K\bar{K}$ threshold (Alston-Garnjost 1971) predicted from earlier $K\bar{K}$ studies (Hyams 1970, Beusch 1970).

$K\bar{K}$ Cusp Effect. Fig. 2 shows some of the data from a 7 GeV/c bubble chamber experiment (Protopopescu 1972) with results not only for elastic $\pi\pi$ scattering from $\pi^+p \to \pi^+\pi^-\Delta^{++}$, but also inelastic $\pi^+p \to K^+K^-\Delta^{++}$. The $\pi\pi$ cross section was found to decrease rapidly in the region near 980 MeV, as shown by the mass spectrum both in the physical region and extrapolated to the pole. Since only S and P waves are important in this region, it is clear that the amplitude for at least one of these two waves is falling rapidly.

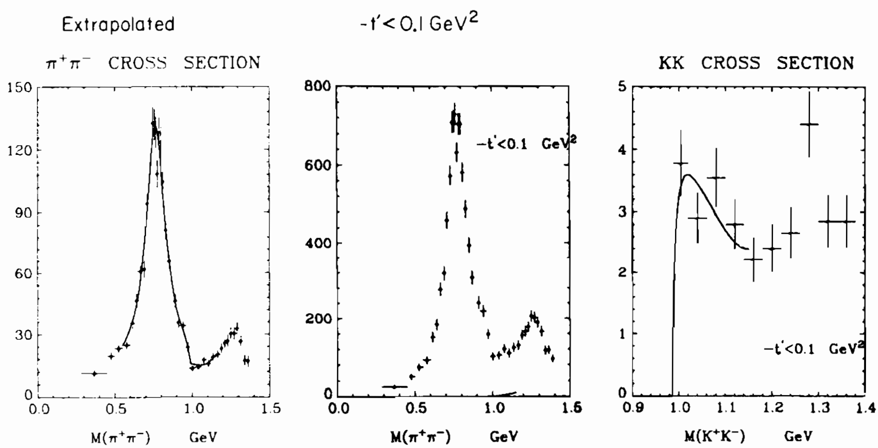

Fig 2. Cross sections at small t and extrapolated to the pion pole for $\pi^+p \to \pi^+\pi^-\Delta^{++}$ and $\pi^+p \to K^+K^-\Delta^{++}$ at 7 GeV/c (Protopopescu 1972). The curves show the result of the fit described in Table 1.

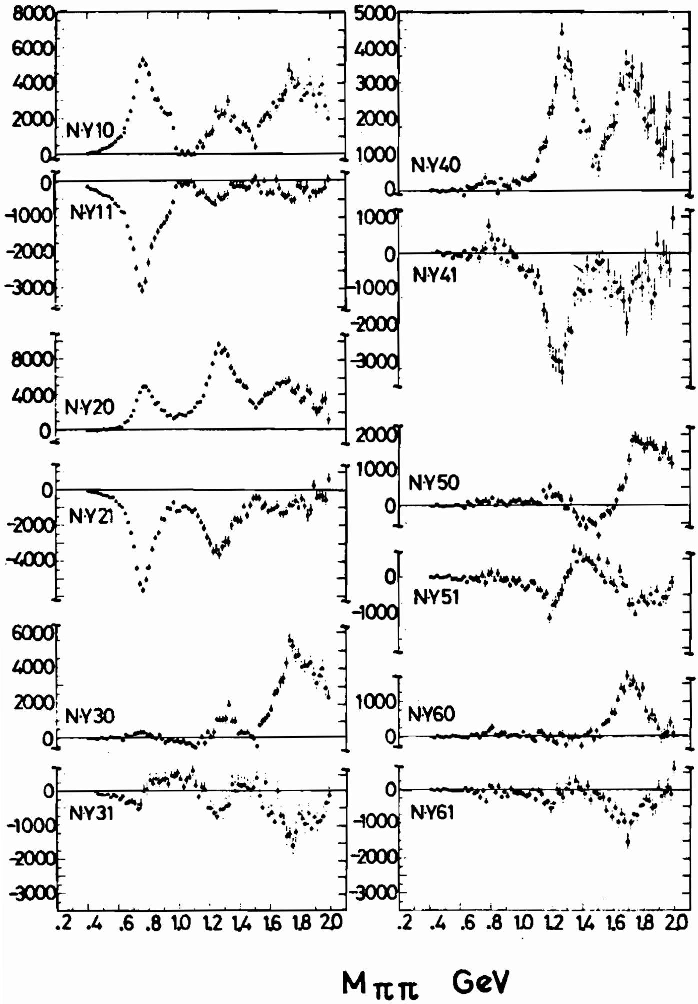

Fig. 3. Corrected unnormalized moments $N\langle Y_\ell^m \rangle$ for the $\pi\pi$ angular distribution from $\pi^- p \rightarrow \pi^- \pi^+ n$ at 17 GeV/c (Grayer 1972a).

This effect was also found at 17 GeV/c by the CERN-Munich Group with their wire-chamber spectrometer (Grayer 1972a). With more than 300, 000 good events for the reaction $\pi^- p \to \pi^+\pi^- n$, the statistical errors for the moments are indeed small, Fig. 3. The unnormalized moment $N\langle Y_2^0 \rangle$ is proportional to the P-wave contribution in the mass range of interest; near 980 MeV this distribution is rather smooth, so it must be a sudden loss of S-wave amplitude which causes the drop in cross section. This qualitative picture is consistent with the Y_1^0 moment which falls rapidly to zero in this mass region (Flatté 1972).

To get a quantitative fit, Protopopescu (1972) used the energy dependent parametrization outlined in Table 1. In particular, for the I = 0,S-wave a 2 x 2 M matrix was used to describe the coupled $\pi\pi$ and $K\bar{K}$ channels. With 24 free parameters, fits were made to 171 data points: the extrapolated cross sections and moments up to Y_6^0 over the $\pi\pi$ mass range 550 MeV to 1150 MeV, as well as the K^+K^- data of Fig. 2. The extrapolated $\pi^+\pi^-$ cross sections were obtained using Dürr-Pilkuhn form factors, while the moments were extrapolated linearly in t. Although this is a standard form of extrapolation, it is clear that the method is not perfect since ρ-ω interference effects remained in the extrapolated data. Quite reasonable fits to the data were obtained with χ^2 values in the region 150 to 160 for 147 degrees of freedom, the exact values depending on slight variations of the parametrization.

The results for δ_0^0 are shown in Fig. 4; below the ρ meson the fits give values similar to those obtained previously by Baton (1970) and Baillon (1972). From the ρ up to about 900 MeV, the fit follows the old down solution, but from 900 to 1000 MeV, the phase shift increases rapidly to the final value of about 200°. While this solution is in disagreement with the results of Baton, one of the Baillon points lies very closely to the curve in this region

Table I. Parametrization of partial waves.

Partial wave	Parametrization	Number of free parameters
I=0 s wave	2X2 M-matrix coupling $\pi\pi$ and $K\bar{K}$ channels	7
I=1 p wave	ρ resonance + background, both become inelastic at 900 MeV	7
I=0 d wave	f_0 resonance coupled to $\pi\pi$ and $K\bar{K}$ + background which becomes inelastic at 900 MeV	5
I=1 f wave	Elastic g resonance + background which becomes inelastic at 900 MeV	5
I=2 s wave	$\eta_2^0=1,\ \delta_2^0= q \sum_{n=0}^{5} c_n q^{2n}$	0
I=2 d wave	$\eta_2^2=1,\ \delta_2^2 = aq^5$	0

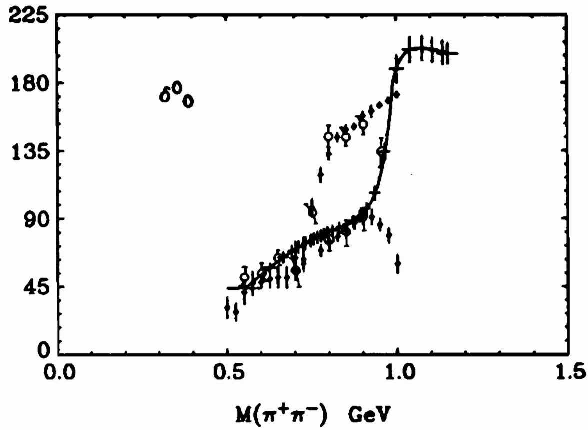

Fig. 4. Phase shifts for I = 0, S-wave $\pi\pi$ scattering: line and crosses Protopopescu (1972), solid dots Baton (1970), open circles Baillon (1972).

Fig. 5 compares the Protopopescu δ^0_0 results with various theoretical solutions collected by Schmid at the Amsterdam Conference (1971). The authors of these theoretical curves used dispersion relations, crossing, unitarity, and so on, to get self-consistent solutions for the highly interlocked $\pi\pi$ system. The Protopopescu results follow most closely the Morgan-Shaw (1970) solution BD1. For a recent discussion of theoretical constraints see Basdevant (1972).

Pole Description. The Protopopescu parametrization gives two poles on the second sheet of the complex energy plane, with parameters shown in Table 2. While a simple Breit-Wigner has a pole at $M_o - i\Gamma/2$, the pole position for relativistic forms is somewhat displaced. Experience with the πN system indicates that the pole location may be better determined than M_o and Γ. Fits to the πp mass distribution in the Δ region gave resonant masses from 1231 to 1234 MeV and widths from 112 to 120 MeV depending on the particular formula used (Particle Data Group 1971). The location of the S-matrix pole was found to be more stable: $M - i\Gamma/2 = 1211 - 50i$ MeV, with different fits agreeing to within 1/2 MeV (Ball 1972); a very detailed discussion of various fits is given in the most recent Review of Particle Properties (Particle Data Group 1972). One might suppose that the poles of the $\pi\pi$ amplitude will also be more stable than simple Breit-Wigner descriptions.

An alternative solution was recently obtained by Protopopescu (1972); it does not contain the ϵ pole and the existence of an ϵ resonance thus remains in doubt. The final interpretation of this effect must await further analysis and will probably require additional low mass data.

Table 2. Poles in the Complex Energy Plane for the I = 0, S-Wave $\pi\pi$ Scattering Amplitude of Protopopescu (1972)

ϵ	600	-	250i
	±100		±70
S^*	980	-	37i
	±7		±8

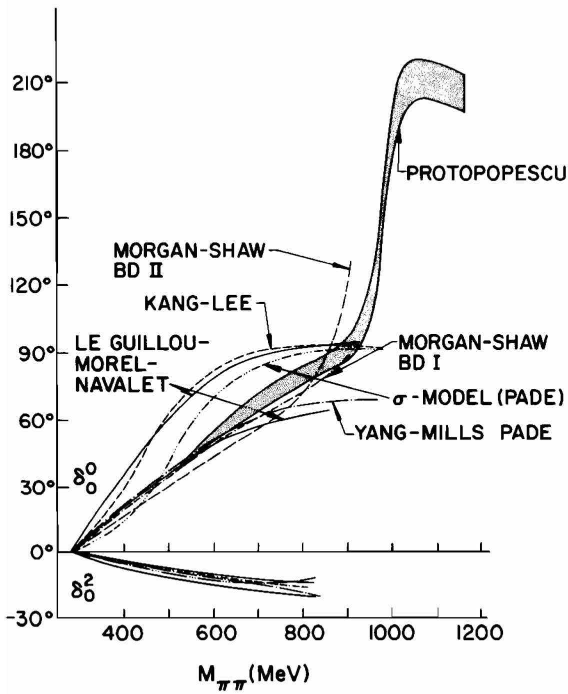

Fig. 5. Comparison of the Protopopescu phase shift with theoretical work compiled by Schmid (1971).

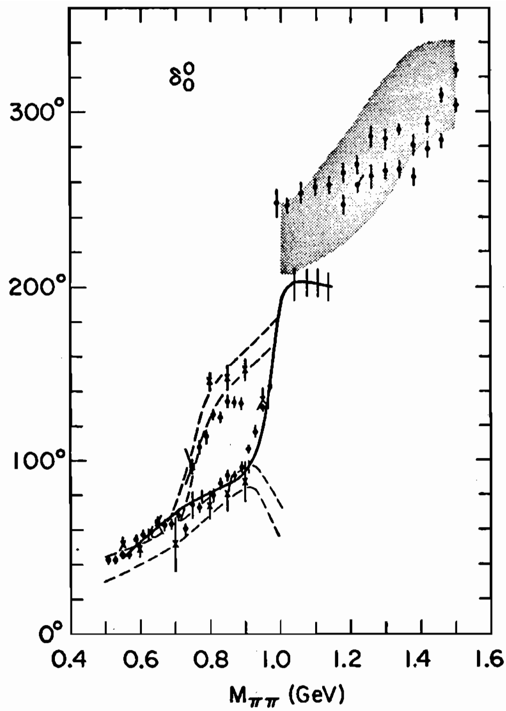

Fig. 6. Summary of I = 0, S-wave phase shift results: solid curve Protopopescu (1972), dashed curve Baton (1970) limits, x's Baillon (1972), solid points Grayer (1972a), shaded band Carroll (1972).

The results of the CERN-Munich Group (Grayer 1972a) for the I = 0, S-wave phase shift are shown in Fig. 6. While some points are shown along the up solution, the 900 to 940 MeV region contains no up solution, and the data from 820 to 900 MeV give very poor fits to the up solution. A simple requirement of continuity thus eliminates the up solution from this analysis as well.

Odorico Zeros. It was suggested by Odorico (1972) that the effects seen in $\pi\pi$ scattering near 980 MeV come from straight-line zeros in the Mandelstam plane, rather than $K\bar{K}$ threshold effects. Pennington and Protopopescu (1972) have used the phase shift results to find the zeros shown in Fig. 7. These zeros do not turn out to be straight lines, and as discussed by Fujii (1972), it is difficult to see how the Odorico zeros could give such sharp structure as a function of $\pi\pi$ mass.

$\pi^0\pi^0$ Results. Two experiments on the reaction $\pi^- p \rightarrow \pi^0\pi^0 n$ were presented to this conference. Skuja (1972) at Berkeley studied the reaction from 1.6 to 2.4 GeV/c. At these low

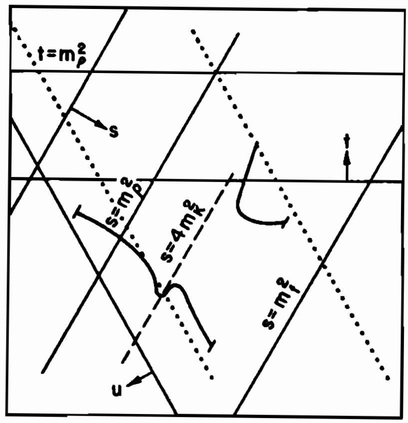

Fig. 7. Mandelstam plane for $\pi^+\pi^-$. The zeros determined from the phase shift analysis (Pennington and Protopopescu 1972), heavy curved lines, are compared with the Odorico (1972) zeros, dotted straight lines.

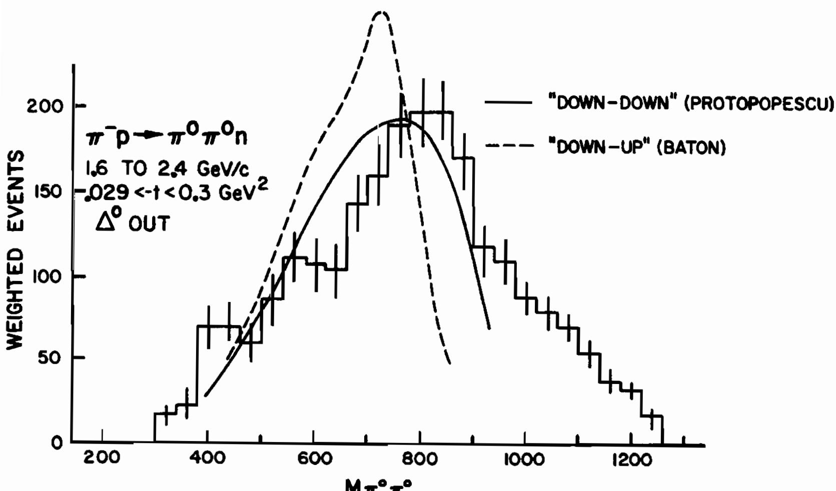

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Fig. 8. Comparison of $\pi^0\pi^0$ mass spectrum with that expected from S-wave phase shift solutions; the curves are normalized to the events between 400 and 940 MeV (Skuja 1972).

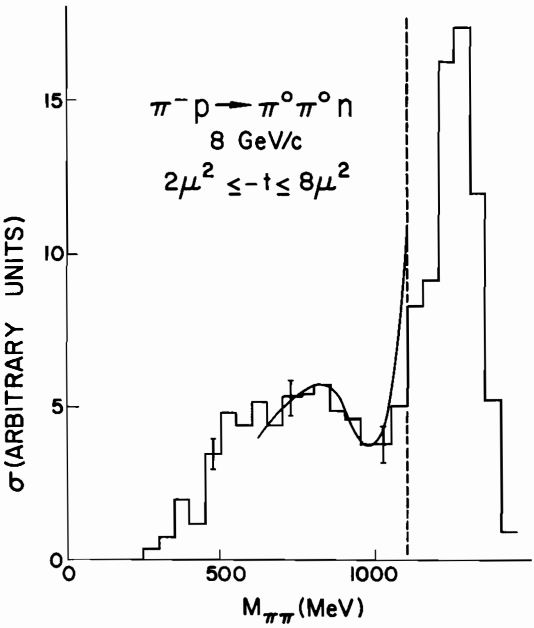

Fig. 9. Corrected $\pi^o\pi^o$ mass spectrum of Apel (1972) compared with that expected from the Protopopescu (1972) phase shift (the full t range is not accepted above 1100 MeV).

energies the reaction is dominated by Δ^o production, and one must cut hard to eliminate Δ effects; further, t_{min} is quite large. A marked enhancement is observed in the region above 700 MeV, Fig. 8. The solution of Protopopescu (1972) follows the data rather well in the region above the ρ, while the old down-up solution of Baton (1970) does not.

The same reaction was studied by a Karlsruhe-Pisa Collaboration (Apel 1972) at 8 GeV/c. The mass spectrum is shown in Fig. 9; it agrees reasonably well with the distribution calculated for one pion exchange using the Protopopescu phase shifts with Benecke-Dürr form factors.

High Mass Region. Above 1 GeV the I = 0, S-wave phase shift continues to increase, Fig. 6. As the mass increases, one must include more and more partial waves, each with uncertain inelasticity, and the results become less reliable. However, several groups (Beaupre 1971, Carroll 1972, Grayer 1972a, Gaidos 1972) are in general agreement that the S-wave amplitude is quite large, near 90^o (270^o), in the region of the f meson. The Protopopescu phase shift levels off near 210^o above 1 GeV, disagreeing with this general consensus, perhaps due to

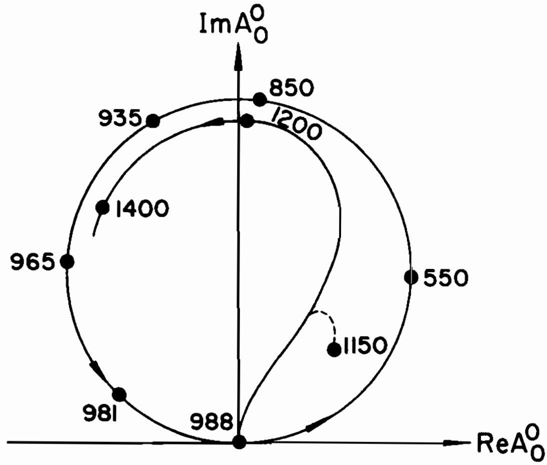

Fig. 10. Argand plot for I = 0, S-wave $\pi\pi$ scattering.

an inadequacy of the energy dependent parameterization. Lipkin (1972) has a quark model with two L = S = 1 states, J = 0 and 2, which interfere in a clever manner so as to reduce the J = 2 bump at $\cos\theta = 0$, as seen experimentally in the f region.

Argand Plot. Fig. 10 summarizes in a qualitative way the I = 0, S-wave $\pi\pi$ amplitude. Starting from the origin, the phase works its way up to 90° near 850 MeV. It then starts downward, moving faster and faster until it reaches $K\bar{K}$ threshold at which point it jumps off at 90° and becomes inelastic. The phase of 180° at $K\bar{K}$ threshold is taken from the fit of Protopopescu (1972). This phase depends on the particular energy-dependent parametrization used, however, and needs a careful analysis with high statistics and good mass resolution. Fits with other phases at threshold are shown by Flatté (1972). Above $K\bar{K}$ threshold, the amplitude wanders back up to about 90° in the region of the f. It becomes elastic, or nearly so, in this region and continues slowly around the plot.

The 0^{++} nonet expected in the quark model has been the subject of speculation for some time. At present the $\pi_N(975)$ and the strong S-wave $K\pi$ amplitude in the region 1100-1400 MeV are the best candidates for the I = 1 and 1/2 members. The Gell-Mann-Okubo mass formula then predicts that the octet I = 0 member has a mass in the 1200 to 1500 MeV region, in which case

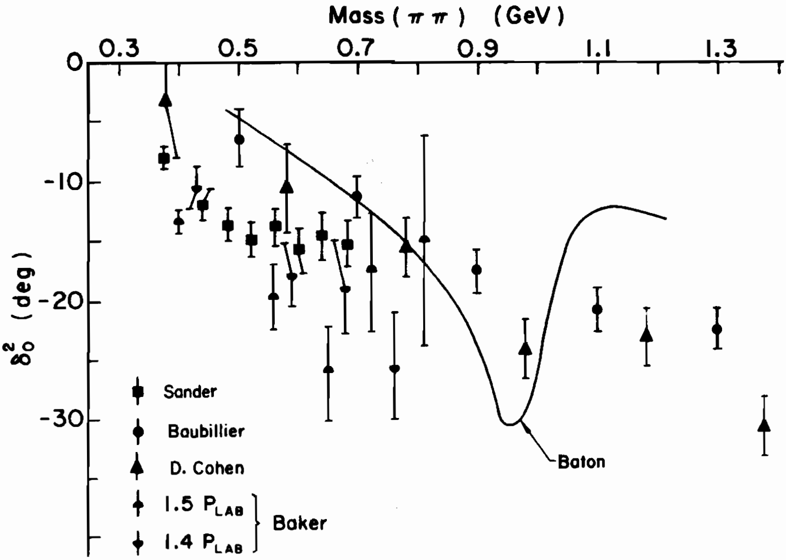

Fig. 11. Results presented to this conference on the I = 2, S-wave phase shift compared with the earlier results of Baton (1970).

the S-wave under the f would be mainly octet and the ε and S^* mainly singlet.

I = 2, S-Wave ππ Phase Shift

Results from four experiments on the I = 2, S-wave phase shift were presented to this conference and are summarized in Fig. 11. Baubillier (1972) and D. Cohen (1972a) find phase shifts of about -6° and -8°, respectively, at the K mass using the reaction $\pi^- d \rightarrow \pi^- \pi^- pp$. Sander (1972) and Baker (1972) obtain -14° and -16° from the reaction $\pi^+ p \rightarrow \pi^+ \pi^+ n$. The differences between experiments are quite large (the cross sections are roughly proportional to the square of the phase shift). Some of the discrepancies might be attributed to the fact that the analyses all assume the cross section to pass through zero at t = 0. The experiment of Baker was performed at 1.5 GeV/c, in the resonance region with large values of t_{min}. Also, the deuterium experiments may be experiencing problems due to the presence of two slow nucleons in the final state.

Until the discrepancies are resolved, one must be cautious in the use of any of these values for δ_0^2. The δ_0^0 analysis of Protopopescu (1972) used the Baton (1970) values for δ_0^2 as input and the δ_0^0 results may move around somewhat as δ_0^2 becomes better known.

Coulomb interference effects were included in the analysis of $\pi^+\pi^+$ scattering made by Sander (1972). The I = 2 phase shifts for both S and D waves were found to be negative.

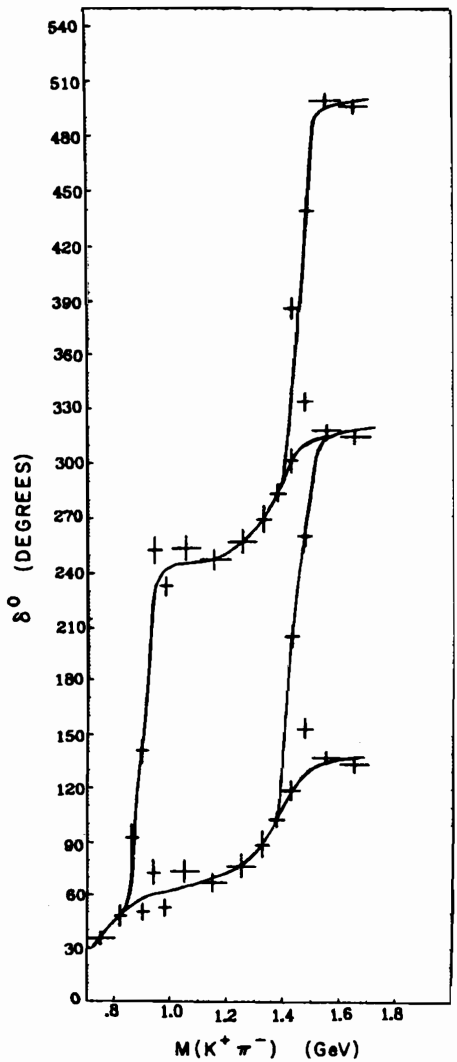

Fig. 12. Kπ S-wave phase shift ambiguities (Firestone 1972).

Kπ S Wave

As for the ππ system, considerable effort has recently gone into understanding the Kπ S wave amplitude (Bingham 1972a). Up-down ambiguities can occur in both the $K^*(890)$ and $K^*(1420)$ regions, as outlined in Fig. 12 (Firestone 1972). The up solutions would correspond to narrow K^* resonances but for several reasons, the smooth down solutions appear most likely:

1) The Kπ system would then be analogous to the ππ system.

2) It seems unlikely that ature would sneak a resonance into a narrow blind spot.

3) Chung (1972) found that if the S wave had a sharp resonance in the 890-MeV region, positivity conditions on the density matrix would be violated.

4) Assuming the P wave in the 890 region to be given by a Breit-Wigner fit to the extrapolated Y_2^0 moment, Matison (1972) found only the down solution to be compatible with the data.

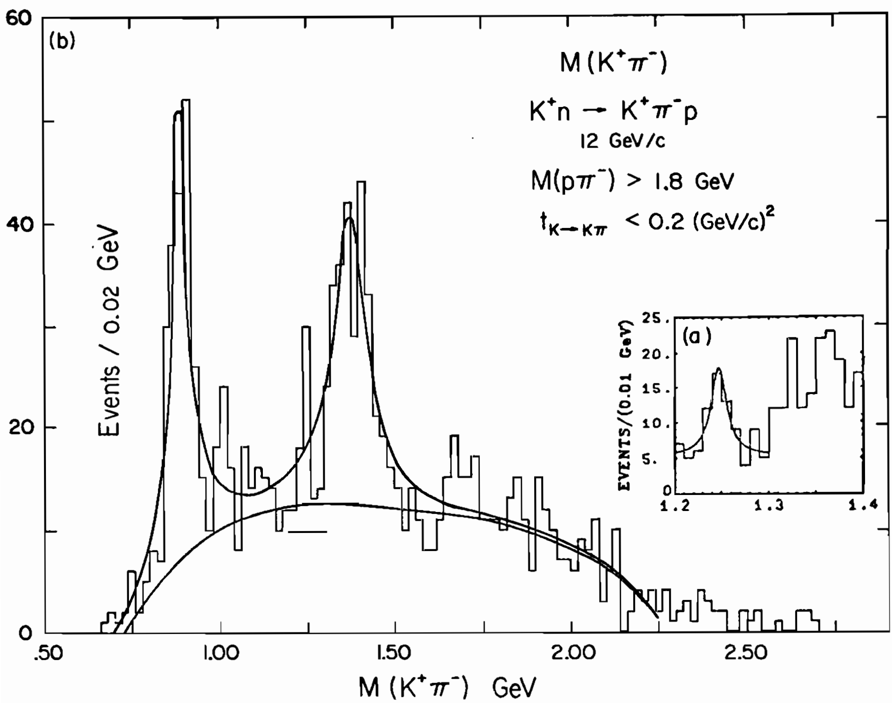

Fig. 13. Fits by a) Firestone (1970a) and b) Slattery (1971) to the $K^+\pi^-$ spectrum of Firestone.

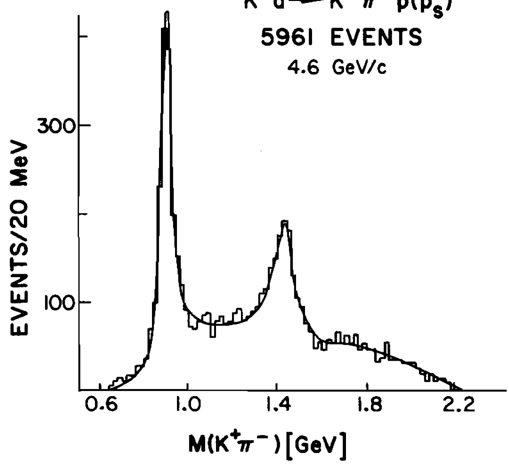

Fig. 14. $K^+\pi^-$ mass distribution from Brussels-CERN-München Collaboration (Buchner 1972); the curve shows the result of a maximum likelihood fit to the Dalitz plot.

There appears to be general agreement that the S wave is strong in the region 1 to 1.5 GeV. A Purdue group (Cords 1972) interpret their data as showing a resonance with mass 1305 ± 30 MeV and width 330 ± 60 MeV. However, the situation is not so clear: as for the ϵ, it is difficult to determine whether the S wave is resonant, and if so, with what parameters. An Argonne-Chicago Collaboration (Yuta 1972) has emphasized the uncertainty in resonance parameters and suggested that the resonant mass could lie anywhere from 1100 to 1400 MeV.

$K\pi$ Bumps

From time to time in the past, bumps have appeared in the region between the $K^*(890)$ and $K^*(1420)$. The data shown in the inset of Fig. 13 (Firestone 1970a) were presented to the Kiev Conference with a claim for a five-standard deviation bump at 1250 MeV with a width of 20 MeV. The Breit-Wigner curve looked very pretty sitting on a background which seemed reasonable at the time. A few months later, however, Slattery (1971) fit the same data to $K^*(890)$, $K^*(1420)$ plus some polynomial background, as shown in the main part of Fig. 13. The overall χ^2 was found to be quite satisfactory but indicated that the "background" in the 1250 region was considerably larger than originally assumed (short horizontal line). The five-standard deviation effect shrunk to less than three-standard deviations. The moral of this story is very important: backgrounds must be estimated carefully before claiming significant structure. New data on the same reaction but at a somewhat lower momentum (4.6 GeV/c) were presented to this conference and are shown in Fig. 14 (Buchner 1972). With roughly three times the events in the 1200-MeV region, no bump is seen with or without t and $M_{p\pi^-}$ cuts.

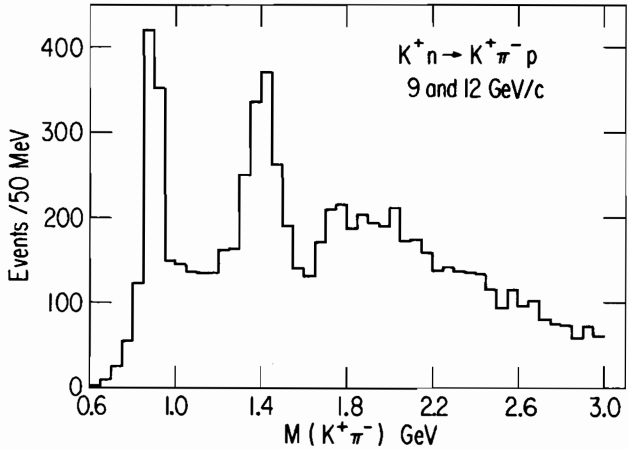

Fig. 15. Compilation of data (Firestone 1971 and Carmony 1971) showing a rise in the $K^+\pi^-$ mass spectrum at 1700 MeV.

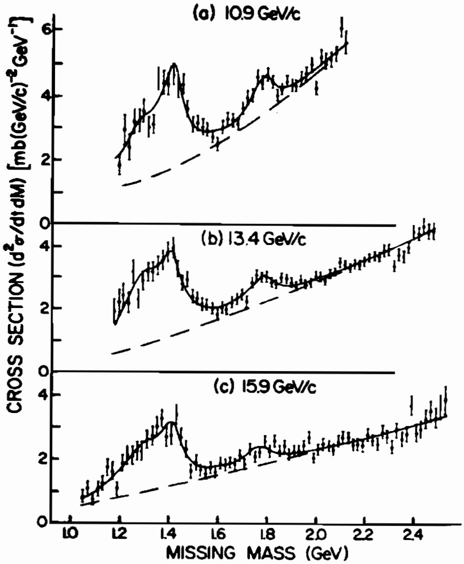

Fig. 16. K^* missing mass spectra in 20 MeV bins for $K^-p \rightarrow K^*p$ (Blieden 1972); the solid curves are the results of fits which include Q(1297), $K^*(1420)$ and L(1767).

High Mass K^*'s

A compilation of $K^+\pi^-$ data for incident momenta of about 10 GeV is shown in Fig. 15 (Carmony 1971, Firestone 1971). In addition to the $K^*(890)$ and $K^*(1420)$ peaks, the data show a rapid increase above 1600 MeV, suggesting resonant behavior. The mass spectrum falls off rather slowly at higher masses, however, indicating that several effects may be present. The signal to background ratio is small and a considerable increase in data will be required before the region is understood.

The Northeastern-Stony Brook Missing Mass Spectrometer was used to search for strange as well as non-strange mesons (Blieden 1972). Fig. 16 shows bumps for the Q, $K^*(1420)$ and L mesons but nothing of significance from the L up to 2.5 GeV. The lack of obvious structure at high masses indicates that it will be harder than ever to find and verify high mass K^*'s, much less determine their quantum numbers.

Diffractive Resonances

The $A_1(1070)$

Eight years ago a $\pi\rho$ enhancement was found near 1100 MeV. The cross section varied slowly with energy, but had a steep t dependence; pions produced it copiously in coherent reactions with nuclei. These properties are characteristic of Pomeron exchange and the effect was hailed as an example of diffraction dissociation (Fig. 17a) predicted by Good and Walker (1960).

Deck (1964) suggested that the OPE diagram of Fig. 17b could be responsible for the enhancement. This diagram gave too wide a mass distribution, but appropriate Reggeization (Berger 1968) resulted in reasonably good agreement with the data.

The spin-parity was found to be 1^+; one expects a definite spin-parity from a bona fide resonance, but generally not from an OPE diagram. Detailed calculations showed, however, that the Deck diagram is in fact predominantly $J^P = 1^+$. Berger (1969) pointed out that this surprising result can be understood by noting that the Deck amplitude is proportional to

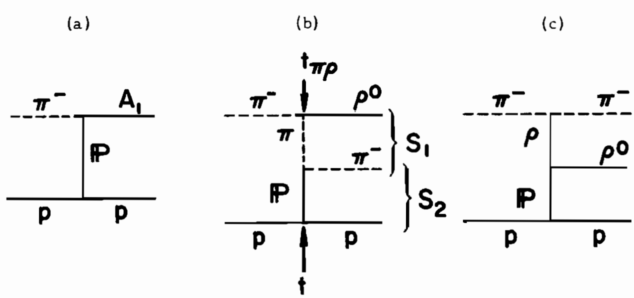

Fig. 17. $A_1 \to \rho^0\pi^-$ production mechanisms.

$$\frac{s_2^{\alpha_P(t)}}{m_\pi^2 - t_{\pi\rho}} .$$

where the notation is given in Fig. 17b. At $t = 0$, $\alpha_P = 1$ and

$$s_2 = s\frac{m_\pi^2 - t_{\pi\rho}}{s_1 - m_\pi^2} .$$

The Deck amplitude then goes as $s/(s_1 - m_\pi^2)$, the pion propagator being neatly cancelled to give a flat S-wave distribution.

Without the pion pole this diagram (Fig. 17b) is no longer so special (Stodolsky 1967); the ρ exchange diagram (Fig. 17c) is roughly as important and should be included in the calculations. This fact is often forgotten, calculations frequently being done with only the π-exchange diagram.

The question of whether the $A_1 \to \rho\pi$ enhancement is just a kinematic effect or a true resonance or some combination has been debated for years. New definitive tests are often advertised, but found to be ambiguous after the expenditure of considerable effort. Recent results suggest that a considerable portion of the peak is probably kinematic effect, in which case the book values for the A_1 mass and width have little to do with 1^+ resonance parameters.

Arguments for a Resonance

1) Quark Model. A nonet with $J^{PC} = 1^{++}$ in this mass region fits well into the quark model ($L = S = 1$). There are candidates for the other members of the nonet, but none of them are sure. The Q is also contaminated by kinematic backgrounds, while the spin parity of the $I = 0$ candidates, D(1285) and E(1422), is not well determined. Rosner and Colglazier (1971) have suggested the M(953) as another possible candidate.

2) Variation with A in Complex Nuclei. Production of A_1's in complex nuclei has an A (atomic number) dependence indicating a mean-free path in the nucleus similar to that for pions (A. S. Goldhaber 1969; Bemporad 1971). This result is difficult to explain in the Deck model (Trefil 1969). Naively, the mean-free path for a $\pi\rho$ system would be about 1/2 that for the pion alone. Even with rescattering and shadowing corrections, one would expect about 46 mb effective cross section for a $\pi\rho$ system (Fishbane 1972) compared with the experimental result 27 ± 4 mb. A. S. Goldhaber (1972) has suggested that the quark-antiquark system of the incident pion is excited by the interaction, but does not break up (with the formation of an additional $q\bar{q}$ pair) while still in the nucleus.

Arguments for Kinematic Enhancement

1) Good Fits. Reggeized Deck calculations can give good agreement with the many mass and angular distributions observed.

2) Helicity Conservation. The angular distributions, both observed (Ascoli 1971, Beaupre 1972) and calculated for kinematic effects (Stodolsky 1967, Donohue 1971) give approximate t-channel helicity conservation. If the enhancement were a resonance one might have expected s-channel helicity conservation (Gilman 1970), as for πp elastic scattering (Halzen and

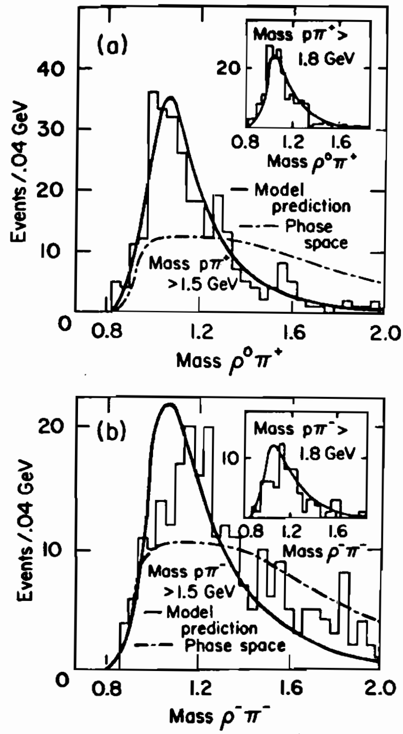

Fig. 18. Mass spectra for $\rho^o\pi^+$ and $\rho^-\pi^-$ compared with the Reggeized Deck model normalized to the $\rho^o\pi^+$ spectrum (D. Cohen 1972b).

and Michael 1971) and ρ photoproduction (Ballam 1972). This argument has a weak spot, however, since $\pi \to A_1$ may be different from these processes because of the spin change, $0^- \to 1^+$.

3) $\pi^-\rho^-$ Enhancement. A comparison was made recently of the reactions

$$\pi^+ p \to \pi^+ \rho^o p$$

$$\pi^- n \to \pi^- \rho^- p .$$

at about 7 GeV/c by D. Cohen (1972b). The πρ mass distributions are shown in Fig. 18 for $t < 0.5$ GeV^2; both singly and doubly charged distributions show low mass enhancements. A Reggeized Deck calculation was made using the π exchange diagrams of Fig. 19 with on-mass-shell cross sections for the elastic and charge exchange πp scattering at the lower vertex. The $\pi^+\rho^o$ curve was normalized to the data, fixing the scale for the $\pi^-\rho^-$ curve. These curves give a reasonable fit to the data, suggesting that the enhancements are largely kinematic in origin.

The doubly charged $\rho^-\pi^-$ enhancement conflicts with the Chew-Pignotti (1968) extended duality notion that a kinematic enhancement implies a resonance; the $\pi^-\rho^-$ bump would then

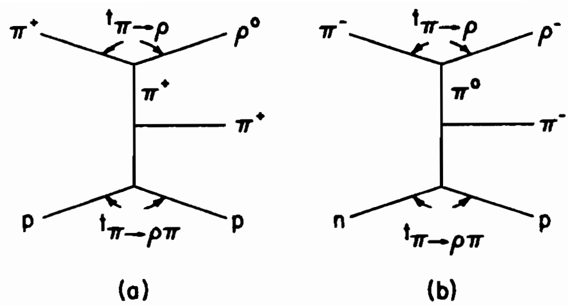

Fig. 19. Diagrams used in model calculations of Fig. 18.

be an exotic resonance. Extended duality was already on shaky ground since the usual duality arguments are made only for the imaginary parts of amplitudes, while the pion exchange term being considered here is mainly real. Also, Berger (1971) was able to construct an explicitly dual model with good agreement with the various observed mass and angular distributions, but no direct-channel poles near $\pi\rho$ threshold. Similar work was presented to this conference by Frampton and Tornquist (1972). Thus, duality does not require that kinematic enhancements be related to resonances, and it seems likely that the doubly charged $\pi\rho$ bump is just an enhancement and not an exotic resonance.

4) Phase Variation. One can look for a rapid change of phase to locate a resonance; indeed a study of the phase should be more sensitive to resonant effects than bump hunting. As emphasized recently by Fox (1972), one expects that if the $\pi\rho$ system is resonant, final state interactions will lead to resonant phase variation even if the $\pi\rho$ system is produced via the Deck mechanism.

A recent partial-wave analysis of the reaction

$$\pi^- p \to \pi^- \pi^+ \pi^- p$$

indicates that there is no rapid change of phase for the A_1, but reassuringly one does find such a behavior for the A_2 (Antipov 1972a, Ascoli 1972c). The data come from bubble chamber compilations and from the CERN-IHEP Boson Spectrometer at Serpukhov; the analysis uses the method developed at the University of Illinois (Ascoli 1970). A maximum-likelihood method is used to fit the complete "decay" distribution, Dalitz and angle variables, of the 3π system. The 3π state is assumed to decay via dipion systems in a two-step decay with the following amplitudes:

$\vert 0^- 0\rangle$	S-wave $\epsilon\pi$ and P-wave $\rho\pi$
$\vert 1^+ 0\rangle$	P-wave $\epsilon\pi$ and S-wave $\rho\pi$
$\vert 2^+ 1\rangle + \vert 2^+ -1\rangle$	P-wave $f\pi$ and D-wave $\rho\pi$
$\vert 2^- 0\rangle$	S-wave $f\pi$ and P-wave $\rho\pi$
$\vert 3^+ 0\rangle$	P-wave $f\pi$ and D-wave $\rho\pi$

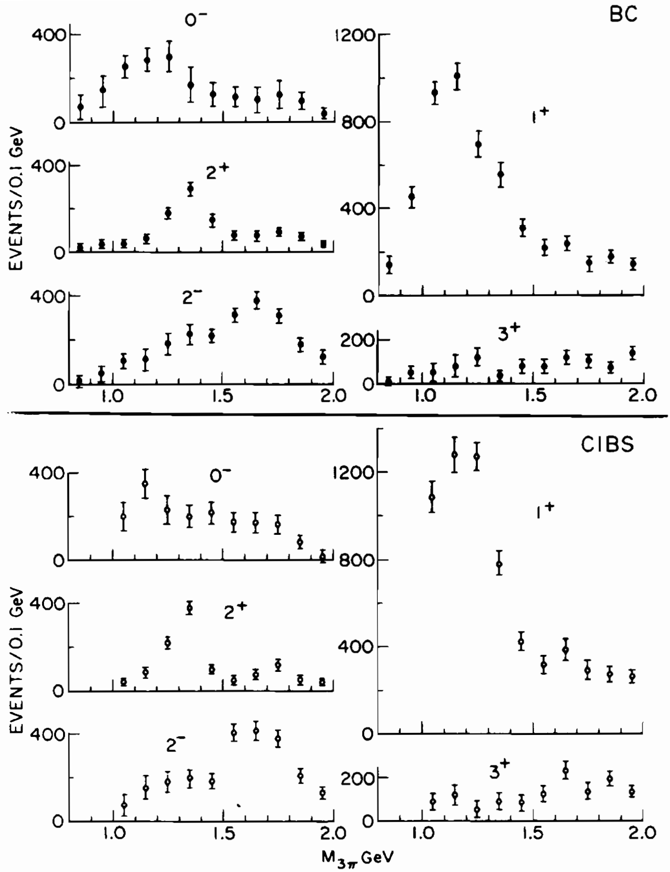

Fig. 20. Contributions of various J^P states to the 3π system for a compilation of bubble chamber (BC) data with average incident momentum 16 GeV/c and the CERN-Serpukhov Boson Spectrometer (CIBS) at 40 GeV/c (Ascoli 1972a).

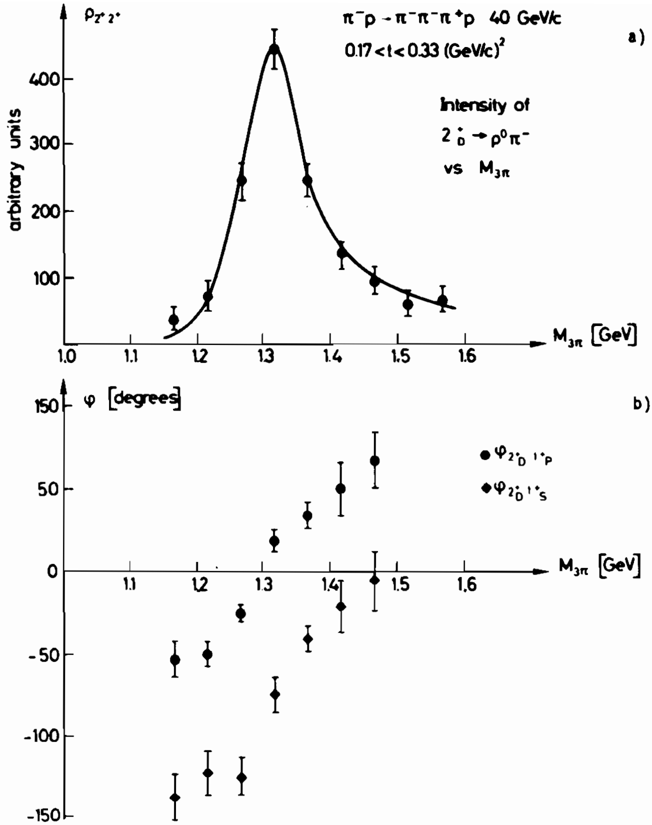

Fig. 21. A_2 results. a) Mass distribution fit by D-wave Breit-Wigner with M = 1315 ± 4 and Γ = 110 ± 15 MeV. b) Phase angles of A_2 with respect to 1^+ background (Antipov 1972a).

Contributions of the various partial waves are shown in Fig. 20 (Ascoli 1972a); the results are very similar at 16 and 40 GeV/c.

The $A_2(2^+ \to \rho^0\pi^-)$ intensity is shown in Fig. 21 (Antipov 1972a), well fit by a D-wave Breit-Wigner with M = 1315 ± 4 MeV and Γ = 110 ± 15 MeV. Also shown in the figure are the phase angles between the A_2 amplitude and the 1^+ amplitudes, as obtained from the off-diagonal elements of the density matrix, $\phi_{ij} = \arg(\rho_{ij})$. A large increase in ϕ is observed in the A_2 region and can be explained by the 2^+ Breit-Wigner amplitude interfering with slowly varying 1^+ amplitudes. Contrary to the oft made assumption that one can neglect interference with background, the data do show strong interference of the A_2 with not only the 1^+, but also 0^- and 2^- amplitudes.

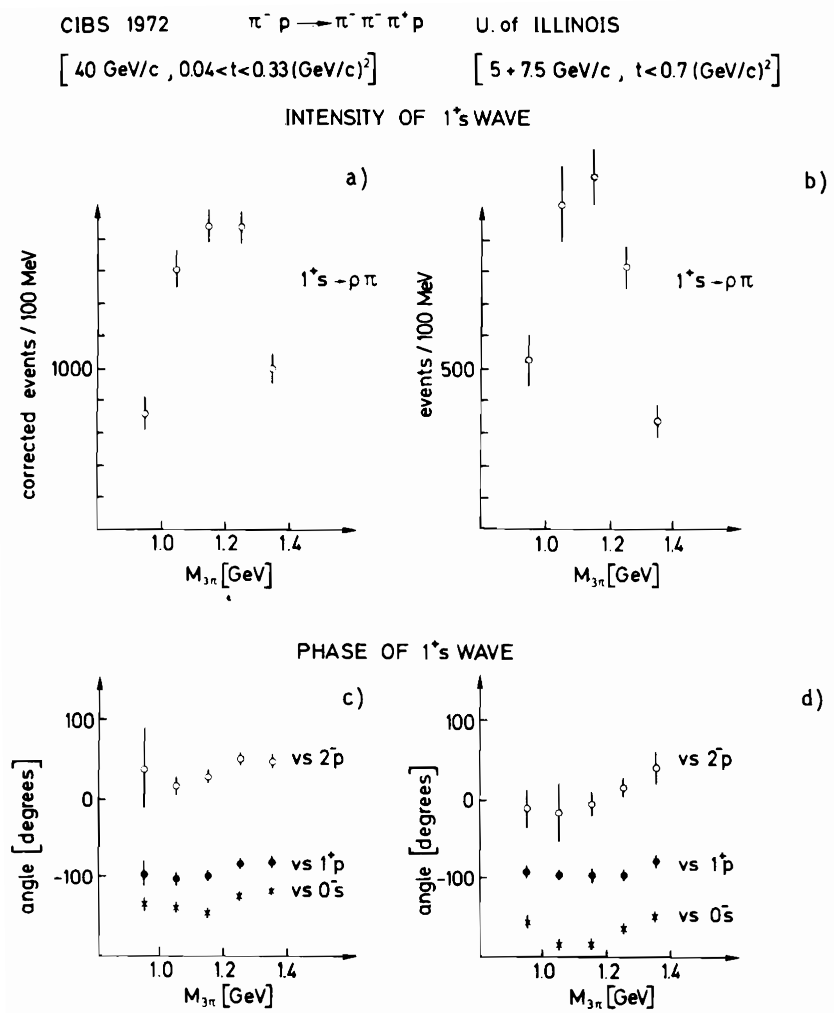

Fig. 22. A_1 results from the analysis of Antipov (1972a).

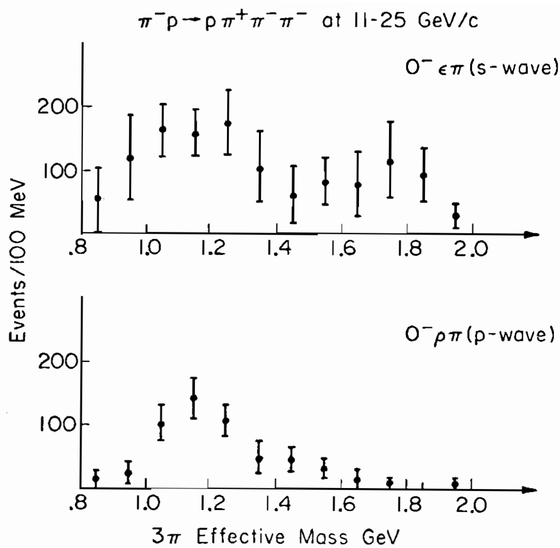

Fig. 23. Intensity of 0^- partial waves (Ascoli 1972b).

Data on the $A_1(1^+ \to \rho^0\pi^-)$ intensity are shown in Fig. 22, together with interference phases (Antipov 1972a). Unlike the A_2, these phases show little variation as $M_{3\pi}$ passes through the A_1 region, suggesting that the $1^+ - \rho\pi$ system is not resonant in this region and the enhancement is completely kinematic in origin. As pointed out by Ascoli (1972c), this interpretation is not without difficulties; for example, the relative phase between A_1 and A_2 amplitudes does not agree well with the expectations of the standard Regge models.

Wright (1972) has shown that it is possible to have a $\rho\pi$ pole for the A_1 and still maintain little phase variation. He assumes that S-wave $\rho\pi$ couples to P-wave $S^*(980)\pi$. The A_1 pole is then partially shielded from the physical region by the cut beginning at $S^*\pi$ threshold (1120 MeV). With the A_1 pole at 1075-164i MeV, he reproduces both the $1^+\rho\pi$ bump and the small phase variation. Including $\epsilon\pi$ as a third coupled channel gives a flat $\epsilon\pi$ spectrum as observed, but this time with the A_1 pole at 975-33i MeV.

To summarize, the phase results have not yet led to a resolution of the A_1 question: not only are the relative amounts of resonance and kinematic enhancement unknown, but even if there is a resonance, its parameters are very uncertain.

5) Possible 0^- Enhancement. The 0^- P-wave $\rho\pi$ distribution shown in Fig. 23 (Ascoli 1972b) peaks up at low mass with roughly the same shape as the A_1, but only 10 or 15% of the intensity. One interpretation of this effect is that the Deck diagrams are contributing to more than just S wave. Berger (1969) predicted such an effect at $t \neq 0$ where $\alpha_P(t)<1$ leads to incomplete cancellation of the pion propagator. One might also imagine that through some inadequacy

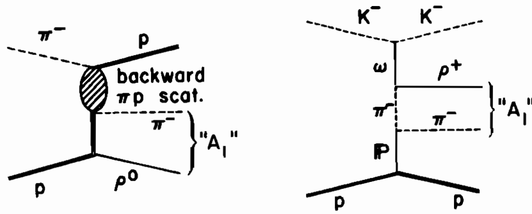

Fig. 24. Processes expected to give low-mass $\rho\pi$ enhancements (Berger 1969, 1971).

in analysis a small fraction of the 1^+ events are leaking into the 0^- results.

A_1 Future

It seems clear that any definitive study of the 1^{++} resonances predicted by the quark model is going to have to come from channels with reduced background. Such channels are more difficult to find than one might imagine. The diagrams of Fig. 24 look to the neophyte to be free of kinematic enhancements. Berger (1971) claims not; he predicts a $\pi\rho$ enhancement in backward scattering with mixed J^P. The second diagram in Fig. 24 will be suppressed at high $\rho^+\pi^-$ mass by the low intercept of the pion trajectory, again yielding a low-mass enhancement. Fox (1972) has suggested that hypercharge reactions such as $K^-n \rightarrow A_1^-\Lambda$ may be the best place to look for an A_1 resonance.

The A_3(1640)

The A_3 is a broad $J^{PC} = 2^{-+}f\pi$ enhancement near threshold. The quark model expects such a state (L = 2, S = 0), and it could be the Regge recurrence of the pion. But the Deck diagrams shown previously for the A_1 apply here also, with the substitution of f for ρ^0. The A_3 is thus saddled with all the uncertainties of the A_1; only in this case the data are more sparse and the background worse.

Fig. 20 (Ascoli 1972a) shows that only the 2^- distribution peaks in the A_3 region, and Fig. 25 shows that this peaking is due to S-wave $f\pi^-$. Dominance of this partial wave for the A_3 was also obtained by Armenise (1972a) using both Chung (1968b) and Zemach (1964) analyses. Upper limits for other contributions to the 2^- peak are (Ascoli 1972b):

$$D \rightarrow \epsilon\pi^- \lesssim 6\%$$
$$P, F \rightarrow \rho^0\pi^- \lesssim 20\%$$
$$D \rightarrow f\pi^- \lesssim 6\%$$

and uncorrelated 3π (flat Dalitz plot and isotropic decay) $\lesssim 20\%$.

The phase of the S-wave $f\pi^-$ amplitude relative to four other amplitudes is shown in Fig. 26 (Ascoli 1972b). As for the A_1, the variation expected if A_3 were resonant is not found. Similar results are obtained at 40 GeV/c (Ascoli 1972a).

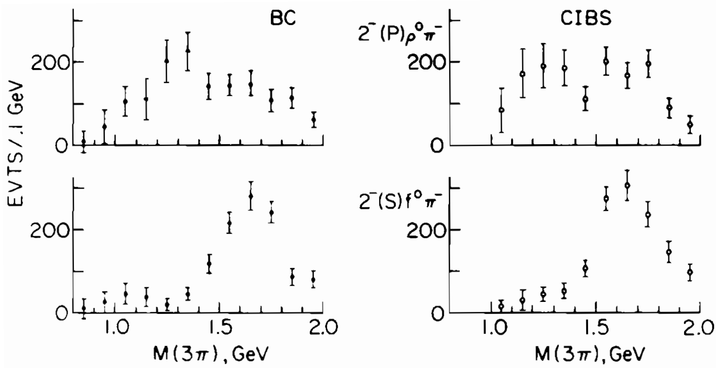

Fig. 25. Intensity of the 2^- partial waves (Ascoli 1972a).

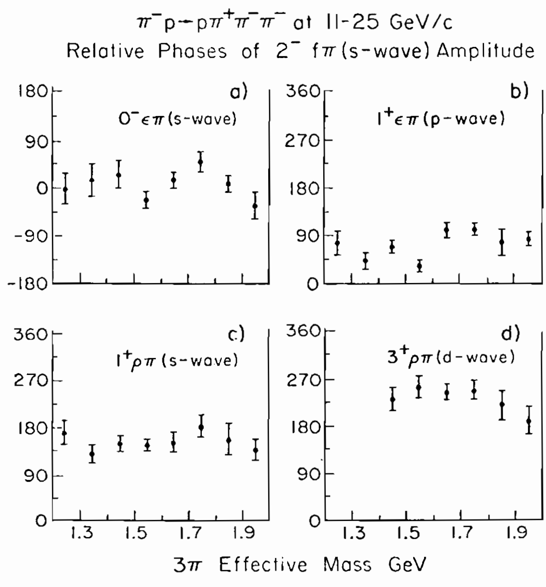

Fig. 26. Relative phase between the A_3 and various background amplitudes (Ascoli 1972b).

The Q_A(1240?)

The strange counterpart of the A_1 has all the troubles concerning kinematic background plus an additional ambiguity: it has the same quantum numbers as the strange member of the B(1235) nonet. Although the B and the A_1 have opposite charge conjugation C (and thus different G parity allowing easy separation), strange mesons are not eigenstates of C. Q_A and Q_B can thus have the same decay modes and decay angular distributions. Further, the strange mesons belonging to the two SU_3 nonets can mix if SU_3 symmetry is broken (G. Goldhaber 1967).

A broad $K\pi\pi$ enhancement in the 1100 to 1500 MeV region has been observed by many experiments (e.g., Bingham 1972b). This enhancement has a rather flat top and is not well fit by a single Breit-Wigner. Fits have been made with two Breit-Wigners (e.g., Firestone 1970b), but the widths vary considerably depending on background assumptions, and the situation is further complicated by the $K\pi\pi$ decay of the $K^*(1420)$. Using SU_3 and $\Gamma(A_1 \to \pi\rho) = 140$ MeV (a very dubious assumption), Fox (1972) predicts $\Gamma(Q_A) = 50$ MeV, in which case only a small part of the Q bump would be Q_A.

Charge Exchange Q. The same group which studied A_1 charge exchange has also looked at Q charge exchange (Werner 1972). Unfortunately, the analysis is made difficult by the considerable background present for both Q^o and Q^{++}. While the $(K\pi\pi)^o$ spectrum is consistent with the amount of Q^o expected from diffractively produced $Q^\pm$, the doubly charged spectrum has at most half the number expected. This says that the Q cannot be described by kinematic models alone. Such a result is to be expected, however, since some of Q^o and $Q^\pm$ may well be associated with the K^* of the B nonet.

Q^o Crossover. A recent experiment on the reactions

$$\left.\begin{array}{l} K_L^o p \to Q^o p \\ \qquad \hookrightarrow K^{*+}\pi^- \\ K_L^o p \to \overline{Q}^o p \\ \qquad \hookrightarrow K^{*-}\pi^+ \end{array}\right\} \to K_s^o \pi^+ \pi^-$$

was reported from SLAC (Brandenburg 1972). The beam had a wide band of momenta and data were collected simultaneously from 4 to 12 GeV/c. The Q events were defined in a crude but straightforward way: $M_{K\pi\pi} = 1.1$ to 1.5 GeV; $M_{p\pi^+} > 1.34$ GeV; $t' < 0.5$ GeV^2 and $M_{K^*} = 860$ to 920 MeV.

One of the more interesting features of the data is a crossover similar to that observed for elastic scattering. The crossover can most easily be understood in terms of the diffraction production of a resonance with Pomeron and ω exchanges similar to that for elastic scattering. Other interpretations may also be possible, however. The situation is again confused by the likely presence of two or more effects, although the ratio of Regge to Pomeron exchange is found to be independent of $K\pi\pi$ mass in the Q region. Attempts were made to fit the data with Reggeized Deck diagrams, but the calculation did not give the observed cross-section falloff with momentum above 5 GeV/c and was unable to reproduce the variation of slope parameters with $M_{K\pi\pi}$.

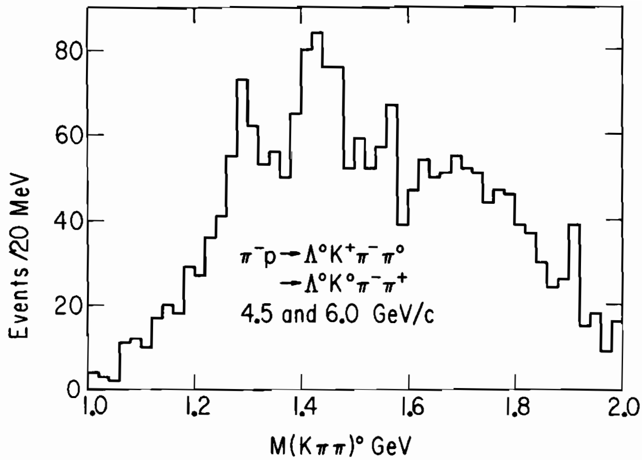

Fig. 27. Nondiffractive Kππ spectrum showing the $K^*(1420)$ and a possible resonance at 1300 MeV (Crennell 1972).

Q Future. Clearly a considerable amount of work is yet required before our level of ignorance can be raised to that for A_1's. Partial wave analysis similar to that for the 3π system is needed. Also data with less kinematic background should be found; as for A_1's, reactions involving strangeness exchange might be a good bet (Fox 1972), e.g.,

$$\pi^- p \to K\pi\pi\Lambda.$$

Such Kππ spectra have been obtained by Crennell (1972) for 4.5 and 6 GeV/c incident momenta; the combined spectrum is shown in Fig. 27. In addition to the $K^*(1420)$, they find a bump at 1300 MeV with a width of about 60 MeV. Although the significance is only 3 standard deviations, it is tantalizing and further work is clearly needed.

Q production from a polarized target was suggested by Fox (1971) as a way to tell whether the Q is kinematic enhancement or resonance; the idea is sketched in Fig. 28. It is an oversimplification, however, since the K^* exchange diagram should also give important contributions.

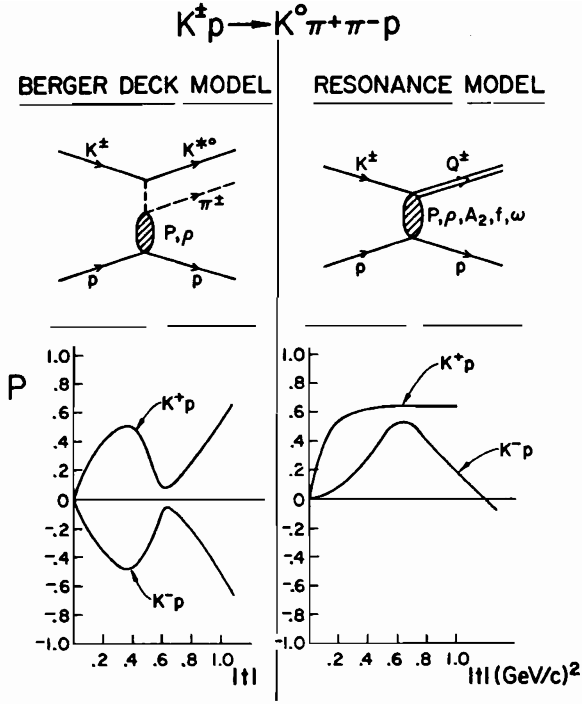

Fig. 28. Proposed test to differentiate between kinematic enhancement and resonant Q using a polarized proton target (Fox 1971).

ρ'(1500)

A new resonance decaying mainly into four pions has been seen in several experiments, and the quantum numbers have been found to be the same as for ρ(770). The evidence appears rather conclusive, although the mass and width are still somewhat uncertain.

Theoretical Expectations

Such a meson has been eagerly anticipated for a number of reasons:

1) Shapiro (1969) calculated the parameters for Veneziano daughters under the f and g: M, $\Gamma_{\pi\pi}$ = 1300, 112 and 1670, 14 MeV, respectively.

2) The quark model predicts a meson with these quantum numbers at 1450 MeV in a triplet D state (see e.g., Gilman 1972).

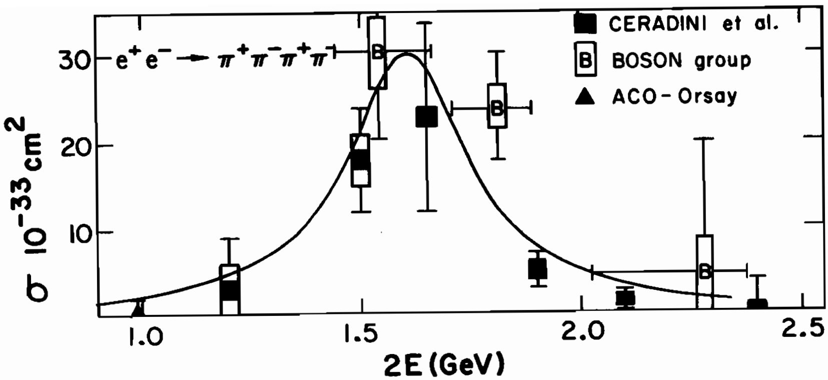

Fig. 29. Colliding beam results for $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ (Ceradini 1972); the curve is a simple Breit-Wigner with M = 1600, Γ = 350 MeV to guide the eye.

3) Several discrepancies in vector dominance calculations have been ascribed to higher mass vector mesons.

4) While the dipole fit to the G form factors of the nucleon suggest a ρ' mass of about 900 MeV, Cordes and O'Donnell (1969) considered the Dirac F form factors and found that a ρ' with $M \sim 2$ GeV can be used to describe the data.

5) Certain Regge-pole fits require a ρ' contribution in the t channel, the classic example being pion-charge-exchange polarization.

Several theoretical arguments suggest that the decay mode to $\pi^+\pi^-$ will be small:

1) Veneziano model (see above).

2) Berger (1971) found that the strength of the P-wave component of the appropriate Drell diagram falls rapidly with $\pi\pi$ mass.

3) Korsström and Roos (1972) consider the pion form factor in the timelike region and conclude that ρ' is not coupled strongly to $\pi^+\pi^-$ but rather to inelastic channels.

Storage Ring Results

The cross section for $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ is shown as a function of energy in Fig. 29 (Ceradini 1972); the data come mainly from the Frascati storage ring, Adone. The cross section peaks up around 1600 MeV, and the authors suggest a width of 350 MeV; as a guide to the eye a simple, but naive Breit-Wigner is shown with these values. Bramón and Greco (1972a) discuss this storage ring result and the implications for the Vector Dominance Model. For further details on $e^+e^- \to \rho'$, see the rapporteur talk of Silvestrini at this conference.

Dipion Photoproduction

An excess of photoproduced dipion events has been observed in this mass range (Bulos 1971, Alvensleben 1971); Fig. 30 shows results obtained at a photon energy near 6 GeV.

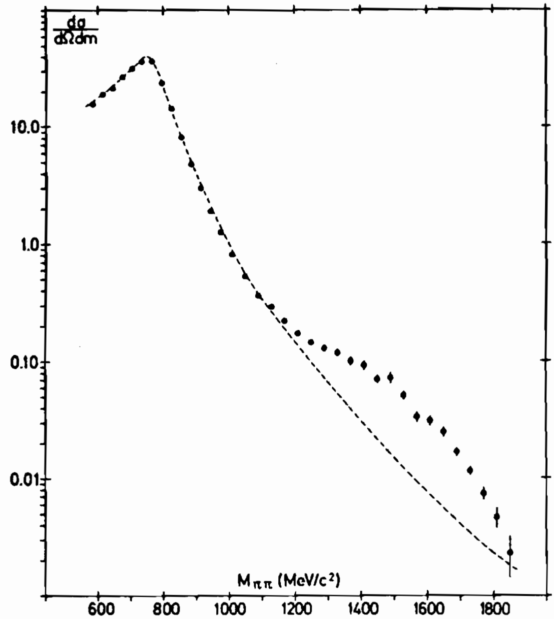

Fig. 30. Mass spectrum for $\pi^+\pi^-$ protoproduction off carbon at 6 GeV/c (Alvensleben 1971).

Although it is hard to know how to draw the tail of the ρ this far from its central mass, the hand-drawn curve looks reasonable and indicates a small excess in the region 1300 to 1800 MeV.

Four-Pion Photoproduction

Data from the SLAC streamer chamber (Davier 1972) are shown in Fig. 31 for the reaction $\gamma p \to \pi^+\pi^-\pi^+\pi^- p$; events with $p\pi^+$ mass in the Δ region have been excluded. An excess of $\rho^o\pi^+\pi^-$ events is seen near 1600 MeV above the peripheral phase space curves. No enhancement was found for a $\rho^o\rho^o$ selection nor for a selection with no combination in the ρ^o. Comparison with the dipion experiments leads the authors to estimate $\Gamma(\rho' \to \pi^+\pi^-)/\Gamma(\rho' \to 4\pi^\pm) \approx 0.14$. Although the $4\pi^\pm$ photoproduced enhancement could be a πA_1 threshold effect (Diebold 1969), the storage ring result cannot be so interpreted.

The 9.3-GeV back-scattered laser beam exposure of the SLAC 82-inch bubble chamber has also yielded information on the ρ' (Bingham 1972c). The reaction

$$\gamma p \to \rho' p, \quad \rho' \to \rho^o\pi^+\pi^-$$

was studied with an average linear polarization of 77% for the beam. To determine the spin

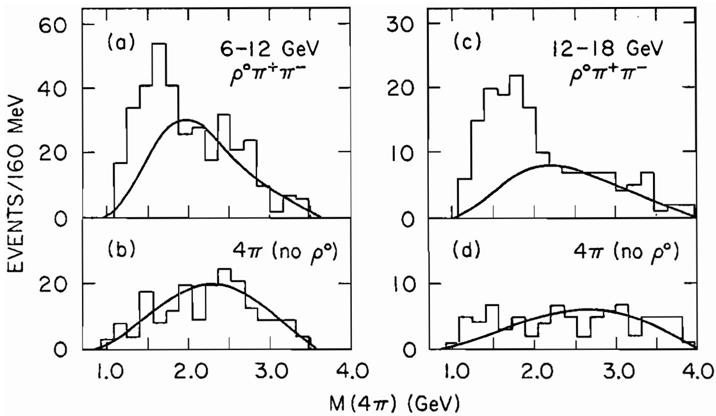

Fig. 31. Four-pion mass spectra from $\gamma p \to \pi^+\pi^-\pi^+\pi^- p$ with Δ^{++} events removed (Davier 1972); curves are drawn for peripheral phase space.

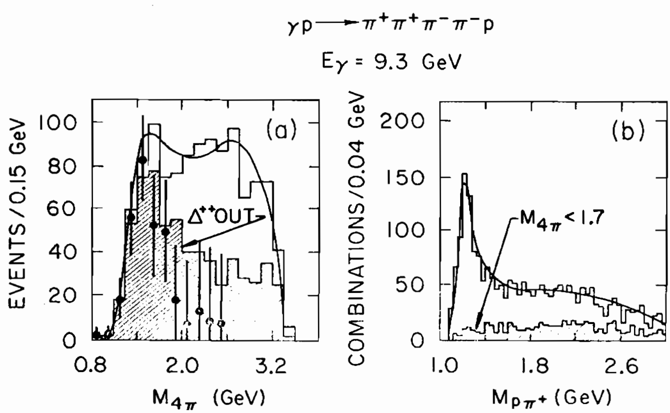

Fig. 32. Backscattered laser beam results (Bingham 1972c). The curves show the maximum likelihood fit and the points indicate the number of s-channel helicity-conserving $J^P = 1^-$ events.

parity the analyzer $\vec{Q} = \vec{\pi}_1^+ + \vec{\pi}_2^+$ is used. This analyzer exhibits a strong $\sin^2\theta\ \cos^2\psi$ dependence in the helicity frame, as expected for diffractive production of a vector meson. Using simple matrix elements, the authors find that $J^P = 1^-$ plus phase space is required to fit the data, other J^P being rejected.

To determine the isotopic spin of the enhancement, they consider the ratio

$$R = \frac{\rho' \to \rho^o\pi^o\pi^o}{\rho' \to \rho^o\pi^+\pi^-} .$$

The data are consistent with zero isotopic spin for the $\pi^+\pi^-$ pair not in the ρ^o, $R \approx 1/2$. The data are inconsistent with other assignments of this isotopic spin, and the ρ' thus has $I^G = 1^+$ and $C = -1$.

The four-charged-pion mass spectrum is shown in Fig. 32. After rejecting events with Δ^{++}, this spectrum shows a peak in the 1600-MeV region. The number of events corresponding to $J^P = 1^-$ with s-channel helicity conservation are shown as the points in the figure; the authors do a maximum likelihood fit and obtain a mass of 1430 ± 50 MeV and width 650 ± 100 MeV. This mass is lower than obtained from the other experiments and the width is greater, but these values are sensitive to the mass dependence assumed for the width. A value of 1.6 ± 0.4 μb was found for ρ' photoproduction with subsequent decay to four charged pions; the slope of the t-distribution is 5.6 ± 0.3 GeV^{-2}. Analysis of the Y_2^2 moments gives two standard deviation upper limits of 20% and 4% for the decays $\pi^+\pi^-$ and K^+K^-, respectively.

The B(1235)

The B(1235) was discovered long ago (Abolins 1963) as a $\pi\omega$ enhancement. Unfortunately, it had a sickly childhood. In one of the early experiments (G. Goldhaber 1965), the ω Dalitz plot had a peculiar distribution, and at the low energies used in the early experiments there was considerable N^* interference which led to speculation as to whether the B existed at all (Chung 1968a). In recent years, the B has been found in many reactions, however, and the early diseases seem to have disappeared.

The only certified decay is into $\pi\omega$. This decay readily leads to the conclusion that $I^G = 1^+$ and $C = -1$. The absence of $\pi\pi$ and $K\bar{K}$ decay modes suggest that $J^P \neq 1^-, 3^-$, etc. Further, if second-class exotics of the quark model are to be avoided, $J^P \neq 0^-, 2^+, 4^+$, etc. Parity conservation eliminates the 0^+ possibility, and the most likely spin-parity assignments for this resonance are $J^P = 1^+, 2^-, 3^+$, etc.

Several contributions on the B were made to this conference (Afzal 1972, Armenise 1972b, Cason 1972, Ott 1972). The most impressive $\pi\omega$ mass distribution, Fig. 33, comes from the Berkeley thesis of R. L. Ott, who studied the reaction $\pi^+ p \to \pi^+ \omega p$ at 7 GeV/c in the SLAC 82" hydrogen bubble chamber. The B signal is very clear with relatively little background. The mass of the B^+ was found to be 1235 ± 5 MeV and the width 147 ± 21 MeV. This width is somewhat broader than the previous world average of 100 ± 20 MeV, but with the present high statistics and low background is probably more reliable. The moments of the ω-decay angular distribution were studied; both the Chung (1968b) and Berman-Jacob (1965) spin-parity analyses gave

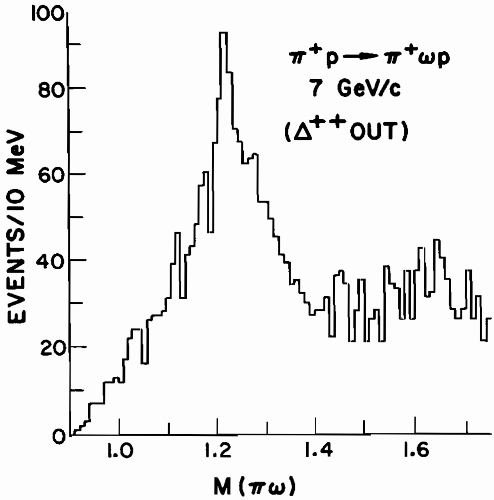

Fig. 33. $\pi\omega$ spectrum showing the B meson (Ott 1972).

$J^P = 1^+$ for the enhancement. Ott finds the $B \to \omega\pi$ decay is mainly S wave.

Many of the analyses (e.g., Frenkiel 1972) of the $\pi\omega$ system tend to give as a possible solution some $J^P = 1^-$ as well as 1^+ in the B region. It is far from clear that such a 1^- contribution is really necessary, but if present it would represent yet another ρ'. In the parallel session, Chung stated that a more complete moments analysis should be made in all B experiments. Eventually one might be able to do a partial wave analysis of the $\pi\omega$ system similar to that done by the Illinois group for the 3π system.

The remainder of the B nonet has yet to be found. The I = 1/2 member may be mixed up in the Q, but the I = 0 members are conspicuously missing.

The D(1286) and E(1420)

The D(1286) and E(1420) have been seen mainly in $\bar{p}p$ reactions, sitting on top of considerable background. Generally these mesons are observed to decay to $\pi\pi_N(975)$. Recent examples of such experiments are Defoix (1972b) for $\pi_N(975) \to \eta\pi$ and Duboc (1972) for $\pi_N(975) \to K\bar{K}$.

From time to time the D has also turned up in double missing mass spectrometer studies of π^-p reactions. Fig. 34 shows data from the Northeastern-Stony Brook group (Thun 1972). A peak at about 1280 is seen, quite compatible with the Table value for the D, while the width 37 ± 5 MeV is somewhat broader than the official 21 ± 10 MeV. The CERN-Serpukhov Boson Spectrometer also has picked up a D signal, both at CERN (Astier 1970) during test runs and

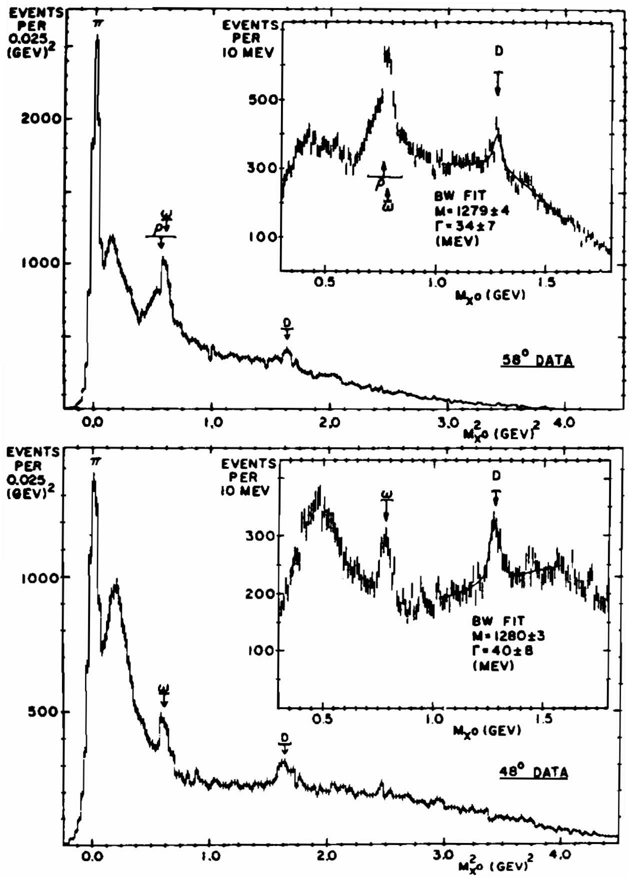

Fig. 34. Double missing mass spectrometer results for the reaction $\pi^- p \rightarrow \pi^- p X^0$ at 13.4 GeV/c; the peak between 0.1 and 0.2 GeV^2 is due to N^* reflections (Thun 1972).

at Serpukhov (Antipov 1972b).

With imagination one might suppose a small bump to be present at 1420 MeV in Fig. 34, perhaps the E. As usual, the evidence for the E is marginal, and one wonders if there is such a meson.

The spin-parity for both the D and E are uncertain with one of the possibilities being 1^{++}, in which case they would fit into the befuddled A_1 nonet. Further work is clearly indicated for both of these mesons; perhaps one could obtain a healthy sample with a suitable double missing mass spectrometer. Since these mesons decay into $\pi_N(975)$, such a study could give valuable information on this somewhat uncertain resonance as well.

Bumps Near 1000 MeV

The $\eta'(957)$

The situation in the 1000-MeV region is summarized in Table 3. The $\eta'(957)$ is well established and the recent experiment of Binnie (1972) sets an upper limit on its width of 1.9 MeV (95% confidence level). Although spin parity 0^- has usually been assumed, the decay distributions could also be given by 2^- for a particular mixture of L = 0 and 2. If the η' were spin 2, it would have a high trajectory and be very important in high energy processes (Zaslavsky 1972). Danburg (1972) considered the decay angular distribution in detail and concluded that 0^- is definitely preferred since it is quite unlikely that production mechanisms would conspire to suppress 2^- angular structure for incident beam momentum over the range 2 to 5 GeV/c.

A narrow effect at 953 MeV was found at Brookhaven (Aguilar-Benitez 1970, Eisner 1972) in the reaction $K^-p \to M^0K^-p$ at incident momenta 3.9 and 4.6 GeV/c, 68 events with $M^0 \to \pi^+\pi^-\gamma$. The characteristics of the M^0 would be consistent with the η' (usually found in the reaction $K^-p \to \eta'\Lambda$), except that the $\pi^+\pi^-$ distribution from the decay does not show the usual peaking in the ρ^0 region. This difference is three or four standard deviations and it is possible that the η' is being observed with a statistical fluctuation.

The $\xi(953)$ was observed in a missing mass experiment using the reaction $pd \to \xi He^3$ (Maglich 1971). In the original publication, the claim was made that the mass scale was understood sufficiently that the difference between ξ and η' masses is significant. A more recent analysis (Brody 1972) indicates that the systematic errors may be large enough to allow compatibility with the η'.

Possible $B_1(1048)$

A group from the Collège de France (Defoix 1972a) presented results to this conference on the reaction $\bar{p}p \to A_2^0\pi^+\pi^-$ at 720 MeV/c incident momentum. They claim to see the decay $A_2 \to B_1(1048)\pi$ with $B_1(1048) \to \omega\pi$ as a five to eight standard deviation effect. As with many spectra obtained from $\bar{p}p$ reactions, the effect is sitting on top of considerable background. Although the authors claim to understand this background, the effect does not appear so significant to the nonexpert. At the parallel session Flatté presented results from a first look at the 7-GeV/c π^+p SUMX tape at Berkeley; he too found some evidence for the $\omega\pi\pi$ decay of A_2^0.

Table 3. Summary of Effects in the 1000-MeV Region

Symbol	M	Γ	J^{PC}	Reaction	Reference
M	940	<10		$\pi^- p \to nX^o$ at 2.4 GeV/c, 5.9σ	Cheshire (1972)
M	953	<10		$K^- p \to MK^- p$ $M \to \pi^+\pi^-\gamma, \pi^+\pi^- \neq \rho^o$	Aguilar-Benitez (1970) Eisner (1972)
ξ	953	<15		$pd \to He^3 X^o$	Maglich (1971)
η'	957	< 1.9	0^{-+}	$K^- p \to \eta'\Lambda$	well established
δ	963	< 6		$\pi^- p \to nX^o$ at 2.4 GeV/c, 5.1σ (related to CERN MMS $\pi^- p \to pX^-$?)	Cheshire (1972)
π_N	975	~60	0^{++}	$K^- p \to (\pi\eta)Y^*_{1385}$ $\bar{p}p \to D+\ldots, D \to \pi_N(975)\pi$	fairly well established
S^*	980	~75	0^{++}	I = 0 S-wave ππ scattering	Protopopescu (1972)
φ	1019	4.4	1^{--}	$K^- p \to \phi\Lambda$	well established
B_1	1048	~55		$\bar{p}p \to \pi^+\pi^- A_2^o$, $A_2^o \to B_1\pi$, $B_1 \to \omega\pi$	Defoix (1972a)

Neutron Missing Mass Results

Possible new mesons in the 950-MeV region have been reported by Cheshire (1972) from a neutron missing mass experiment at Argonne; the reaction $\pi^- p \to X^o n$ was used at 2.4 GeV/c very close to t_{min}. Fig. 35a shows that the missing mass distribution obtained before making cuts is quite smooth, indicating that subsequent structures do not come from systematics such as neutrons reflected from concrete blocks, rate effects, etc. Events with one charged particle through a forward set of counters and a second charged particle to the side exhibit two narrow bumps above the smooth quadratic background in Fig. 35b, M(940) and δ (963). Making additional cuts on the relative azimuthal angles enhances the 940 peak but suppresses the 963. The significance quoted for these peaks is 5 or 6 standard deviations. Using the known η' decay properties, cuts were designed to enhance the η' signal, as shown in Fig. 35d. The $\delta^o(963)$ found in this experiment could be related to the $\delta^-(962)$ found by the CERN missing mass spectrometer (Kienzle 1965), although this interpretation should be viewed with caution since several experiments (e.g., Banner 1967, Abolins 1970 and Anderson 1971) were unable to find the effect. The neutron missing mass group has also found evidence for a narrow state at 1150 MeV (Jacobel 1972).

Another neutron missing mass experiment (Binnie 1972) also observed forward neutrons, but very close to threshold. The mass distribution was obtained by sweeping the beam momentum rather than observing a time-of-flight spectrum as was done by Cheshire (1972). Peaks were found at the ω, η' and φ masses, Fig. 36, but no sign was found for the bumps claimed by

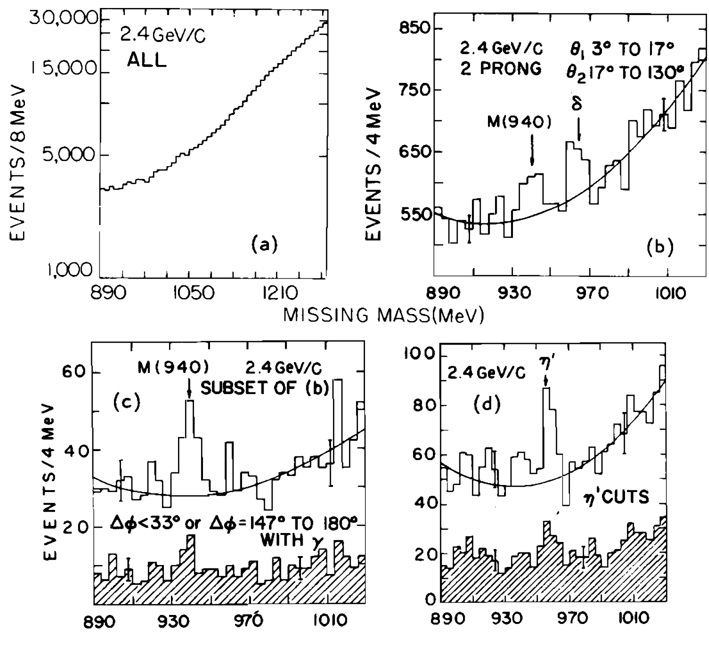

Fig. 35. Missing mass spectra from $\pi^- p \to nX^0$ very close to t_{min} at 2.4 GeV/c (Cheshire 1972); the curves are quadratic fits to background.

Cheshire, even after making cuts similar to the Argonne experiment.

Evidence Against A_2 Splitting

History

A_2 splitting was first taken seriously when the CERN Missing Mass Spectrometer (MMS) Group published the mass spectrum shown in Fig. 37 (Chikovani 1967). The data were obtained from recoil protons near the Jacobian peak (maximum lab angle) for incident π^- at 6 and 7 GeV/c. Although it was found necessary to shift the mass scale for the 1965 spectrum (Levrat 1966) relative to 1967 by about 25 MeV, this shift was blamed on uncertainties in the absolute calibration of the beam momentum. The data exhibited a narrow dip in the center of the A_2 peak with χ^2 probability for a Breit-Wigner fit of 0.1%. Better fits to the data were obtained by assuming two peaks or a dipole shape. After folding in the resolution, however, even the dipole fit could not completely reproduce the narrow dip structure, at least some of which must be attributed to statistics.

A similar dip structure was found with the CERN Boson Spectrometer (CBS) by observing

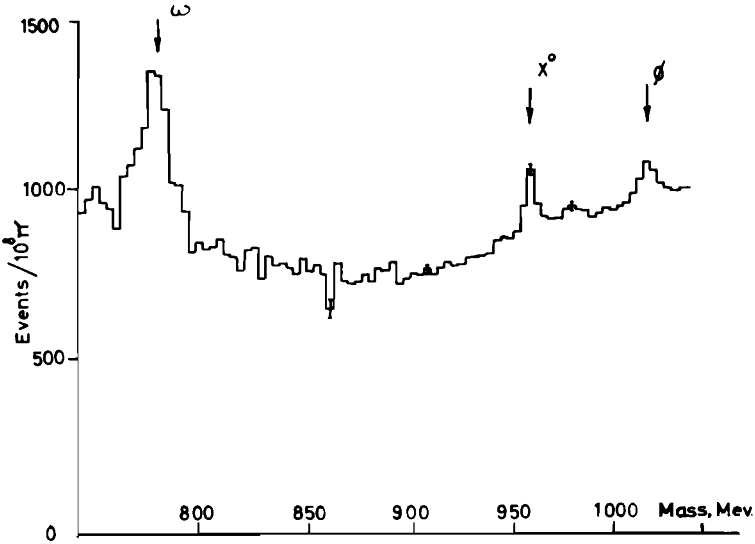

Fig. 36. Missing mass spectra from forward neutrons near threshold for the reaction $\pi^- p \rightarrow nX^0$ (Binnie 1972).

recoil protons near 0° close to threshold (Benz 1968). This data combined with the Jacobian peak results seemed to need either a dipole or two interfering Breit-Wigners for a reasonable fit. Both possibilities required the two halves of the A_2 to have the same spin parity, and indeed most experiments have found 2^+ both above and below the central mass.

Great excitement was generated by the CERN results and several experiments, most with rather low statistics, also claimed to see a dip in the middle of the A_2. Among the more significant of these are the Aguilar-Benitez (1969) results on $\bar{p}p \rightarrow K_1^0 K^\pm \pi^\mp$ and the neutron missing mass experiment of Basile (1970) on the A_2^0. As time went on, however, experiments with high statistics were unable to find any split, but fit a single Breit-Wigner quite well (Alston-Garnjost 1970, Foley 1971, Grayer 1971).

These experiments demonstrated quite conclusively that the A_2 was not a dipole, although the possibility of two interfering Breit-Wigners remained. In particular, by supposing that the amount of coherence and/or the relative phase changed with s, t or reaction, one could obtain various shapes appropriate to the different data (Barnham and Goldhaber 1971). There are two possibilities for interfering Breit-Wigners: a) a wide and a narrow resonance at the same mass or b) two narrow resonances side by side. The second case seems less likely since Lassila and Young (1972) have pointed out that two narrow resonances would not satisfy certain theoretical constraints given by finite energy sum rules and duality.

The two Breit-Wigner hypothesis is flexible enough that it may be difficult to disprove directly. One can make arguments for simplicity, and eventually a phase shift analysis applied

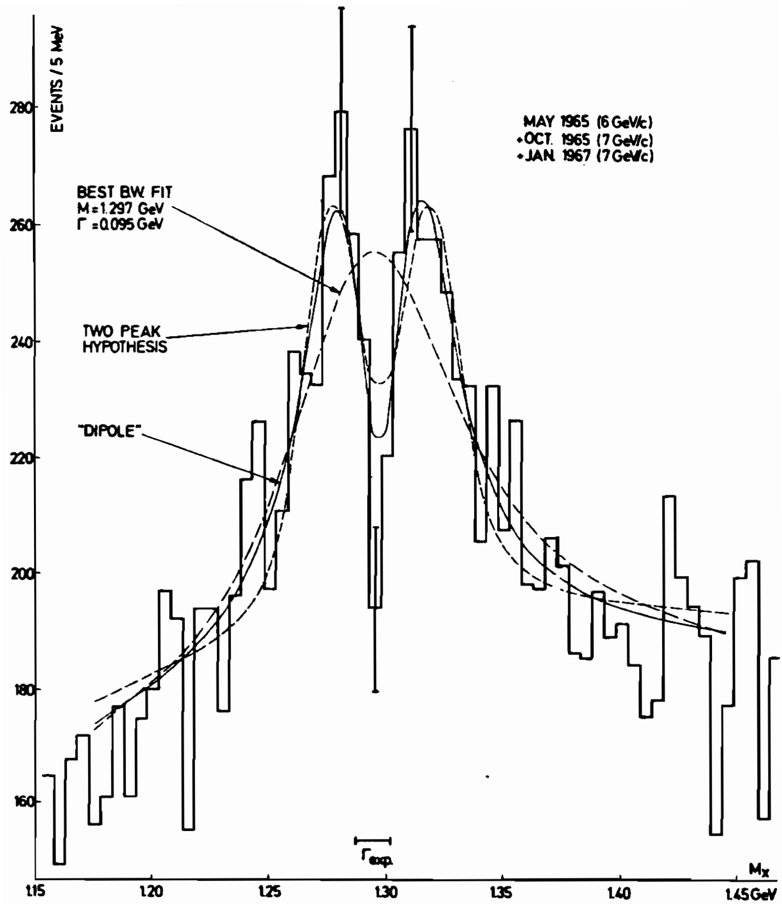

Fig. 37. Results of the CERN missing mass spectrometer in the Jacobian peak region for the reaction $\pi^- p \rightarrow pX^-$ (Chikovani 1967).

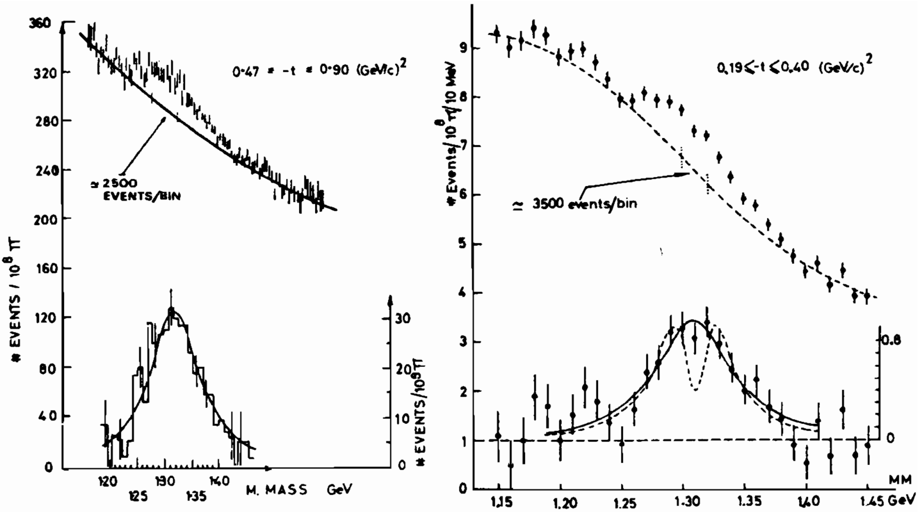

Fig. 38. Missing mass spectrum for forward protons near threshold for $\pi^-p \rightarrow pX^-$ with X^- giving three charged particles; A_2 results shown before and after background subtraction (Binnie 1971a).

to some future experiment with high statistics and good resolution could test for two resonances as a double loop in the Argand plot (Ascoli 1970).

Rutherford Experiment

Efforts were made to reproduce the original results, but failed to do so. Binnie (1971a) repeated the CBS experiment at Rutherford. The results for three forward-going charged particles are shown in Fig. 38 and do not show a dip. Data for one forward-going charged particle were also published from the same experiment (Binnie 1971b); the published results did show some structure but have recently been retracted, an error being found in the data handling programs. All data from this experiment are now compatible with a single Breit-Wigner.

NE-SUNY Experiment

The Jacobian peak region at 5 and 7 GeV/c was re-examined by a Northeastern-Stony Brook Collaboration (NE-SUNY) at Brookhaven. Their results are shown in Fig. 39 (Bowen 1971), together with Breit-Wigner and dipole fits. (Although the dipole shape has been excluded as a fundamental property of the A_2, it is still quite a convenient measure of spectral shapes.) Good fits were obtained for a Breit-Wigner distribution, and the dipole gave quite unacceptable results.

The significance of this type of experiment depends strongly on the mass resolution. The Northeastern-Stony Brook Group calculated resolutions of 16 and 21 MeV FWHM at 5 and

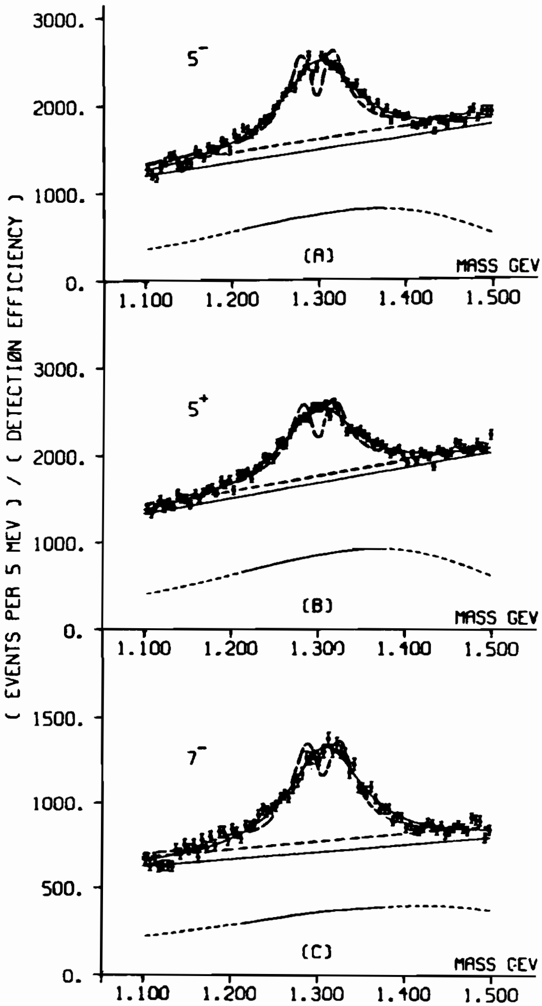

Fig. 39. Missing mass spectrum for Jacobian-peak protons from the reaction $\pi^{\pm}p \rightarrow pX^{\pm}$ at $5(\pi^-)$, $5(\pi^+)$ and $7(\pi^-)$ GeV/c. The straight lines show the linear background found for the Breit-Wigner (solid) and dipole (dashed) fits. The detection efficiencies are shown as the lower lines and are normalized to give the actual number of events detected at 1300 MeV (Bowen 1971).

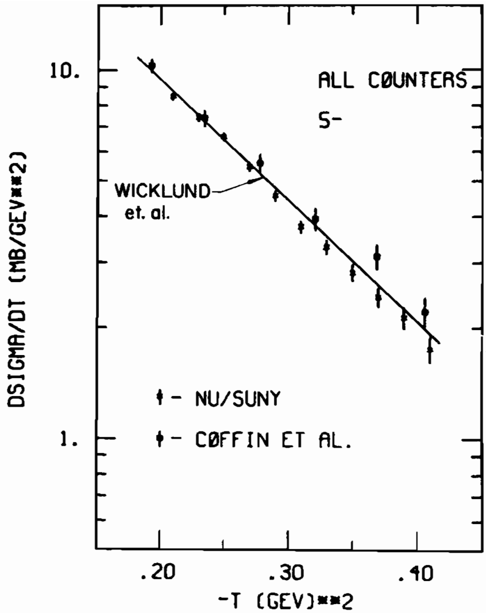

Fig. 40. Elastic scattering check of the Northeastern-Stony Brook experiment (Bowen 1971).

7 GeV/c, respectively. As with most Jacobian peak experiments, this resolution is dominated by multiple scattering of the recoil proton. With the aid of a forward magnetic spectrometer, they were able to determine the experimental uncertainties using elastic scattering events; for example, they determined cos θ by three different methods:

1) $\cos\theta_m \pm \alpha$ — direct measurement;
2) $\cos\theta_1 \pm \beta$ — calculated using p_{beam} and recoil proton energy;
3) $\cos\theta_2 \pm \gamma$ — calculated using angle and momentum of scattered pion.

Taking differences between these values gave peaks with widths related to the errors on the individual determinations:

$$A = \cos\theta_1 - \cos\theta_m \pm a \qquad a^2 = \alpha^2 + \beta^2$$
$$B = \cos\theta_2 - \cos\theta_m \pm b \qquad b^2 = \alpha^2 + \gamma^2$$
$$C = \cos\theta_2 - \cos\theta_1 \pm c \qquad c^2 = \beta^2 + \gamma^2$$

The quantity of interest was then calculated as

$$(\Delta\cos\theta_m)^2 = \alpha^2 = (a^2 + b^2 - c^2)/2 = .0076 \pm .0004 \text{ FWHM}$$

compared with the value .0075 calculated a priori from a knowledge of the experimental equipment.

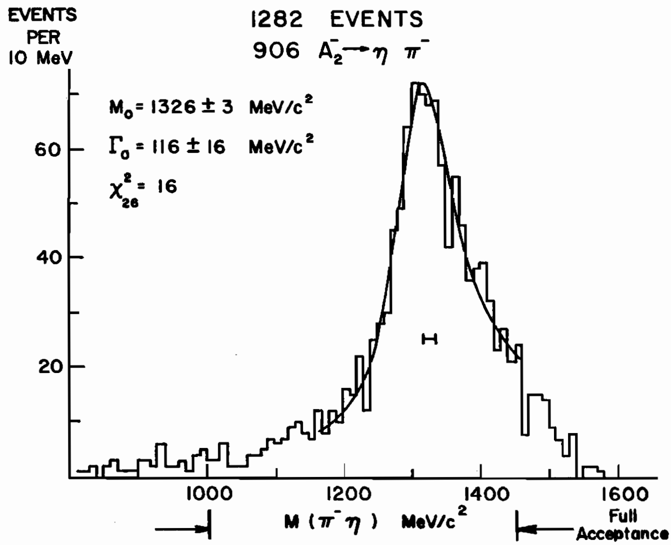

Fig. 41. Mass spectrum for $\pi^- p \to \pi^- \eta p$ at 6 GeV/c (Prepost 1972).

In addition to checking their resolution, the Northeastern-Stony Brook Group performed many other tests of the apparatus. One of these tests was a measurement of $\pi^- p$ elastic scattering, Fig. 40. A smooth differential cross section was obtained in agreement with the recent Argonne results of Wicklund (1972). This test checked the data selection criteria, angle dependent biases, acceptance calculations, and so on. In spite of these checks, the experiment has been under severe attack by Maglich (1972) who claims that their resolution is considerably worse. After a careful reading of his most recent criticism, I can find no substance in this assertion. The Northeastern-Stony Brook Group appear to be doing the analysis in a correct manner, with many more checks of the data and resolution than made for the original CERN experiments.

New Experiments

Three recent experiments from Argonne have also shown a lack of structure. The results of Prepost (1972) are shown in Fig. 41. The reaction $\pi^- p \to A_2^- p$ is observed at 6 GeV/c with a proton telescope near the Jacobian angle and forward optical spark chambers to detect the decay sequence $A_2^- \to \eta\pi^-$, $\eta \to \gamma\gamma$. A very clean spectrum is observed with little background under the A_2. The authors calculate a resolution of 16 MeV FWHM for which the CERN dipole shape would give a valley to peak ratio of 1/2. On the contrary, the data are well fit by a D-wave Breit-Wigner.

Some of the K^+K^- results obtained by our group at Argonne are shown in Fig. 42 (Ayres 1972), uncorrected thus far for spectrometer acceptance. The spectrum rises fast near

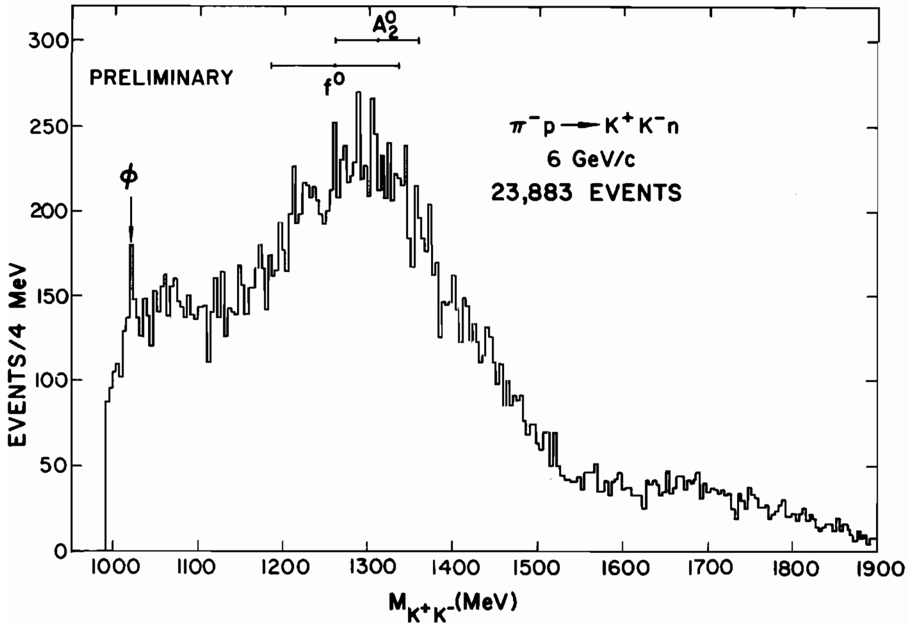

Fig. 42. Argonne Effective Mass Spectrometer results for K^+K^- spectrum, uncorrected for acceptance (Ayres 1972).

threshold, has a narrow peak at the ϕ, levels off and then sweeps up to a broad peak in the region of the f and A_2. At this stage, it is difficult to tell the amount of f and A_2 in the peak, but there are no sharp dips in this region even though the resolution is quite good (~ 8 MeV FWHM, implying a valley to peak ratio of 0.2 for the CERN dipole).

A magnetic spectrometer with wire spark chambers was used by a group from Indiana University to detect the recoiling proton (Ankenbrandt 1972) from $\pi^{\pm}p \to A_2^{\pm}p$ at 4 GeV/c. Minimization of multiple scattering and momentum analysis of the protons resulted in good resolution, 10 MeV FWHM, over a broad range in t. They made several consistency checks of the resolution and of the apparatus in general. Their high-statistics results are shown in Fig. 43a for the entire t range and in Fig. 43b for a t range closer to that used by the CERN MMS experiment. The data fit well to a single Breit-Wigner and strongly reject the dipole.

Toward a Better Understanding of Statistics

The smooth high statistics results are puzzling when one considers all those experiments a few years ago which seemed to verify the split. There is a lesson in statistics to be learned from this puzzle.

Monte Carlo studies (Aguilar-Benitez 1971) were made to understand the statistical significance of $K^*(1420)$ data. Two sets of data corresponding to different final states were

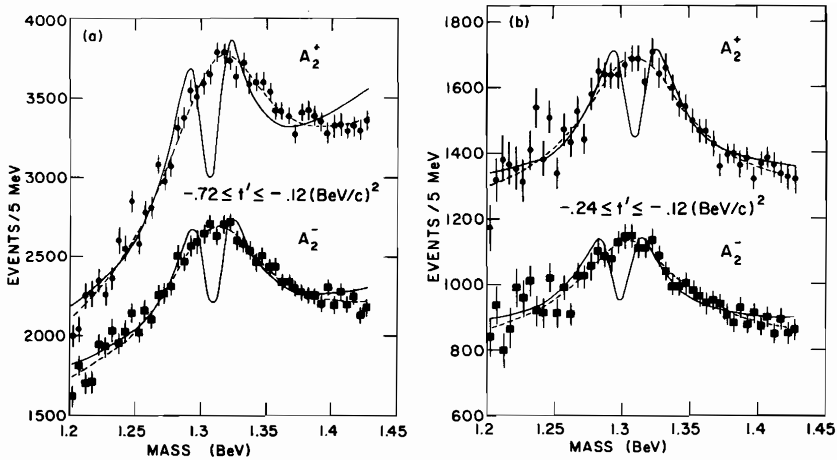

Fig. 43. Missing mass spectrum for $\pi^{\pm}p \rightarrow pX^{\pm}$ at 4 GeV/c (Ankenbrandt 1972); $t' = t - t_{min}$ ($t_{min} = -.06$ GeV^2).

considered. The sample corresponding to $K^-\pi^+$ is shown schematically in Fig. 44. The true shape was assumed to be either a dipole or Breit-Wigner on top of linear background, with an experimental resolution of 17 MeV FWHM. Each of these distributions were generated 50 times, and the Monte Carlo results fit to both Breit-Wigner and dipole. Correlations between the resulting χ^2 probabilities are shown on the scatter plots. Only occasionally did the data derived from the dipole distribution give a decent Breit-Wigner fit. Data generated from the Breit-Wigner distribution, however, often resulted in quite reasonable fits to the dipole, not infrequently even better than the Breit-Wigner fits. Fig. 45 shows similar results for a smaller data sample corresponding to the experimental results on K^o(seen)π^-. The χ^2 probabilities are considerably more spread out in this case. In particular, nearly all of the Monte-Carlo data derived from the Breit-Wigner shape gave quite reasonable dipole fits.

The moral to be learned from these studies is that low statistics experiments must be treated very carefully. In particular, if the results from such experiments are to be considered at all, one must be very careful to include results from all experiments and not just those published because they happen to show an interesting effect. Also, one must be very cautious when dividing data of a particular experiment into several subsets, for example, to search for t-dependent effects; the statistics of the subsets will be poorer, and with enough subsets intriguing fluctuations will appear.

Statistical Significance

To measure the potential statistical significance of a given experiment, Gettner (1972) developed a $\Delta\chi^2$ method. This quantity gives the difference in χ^2 values which would be

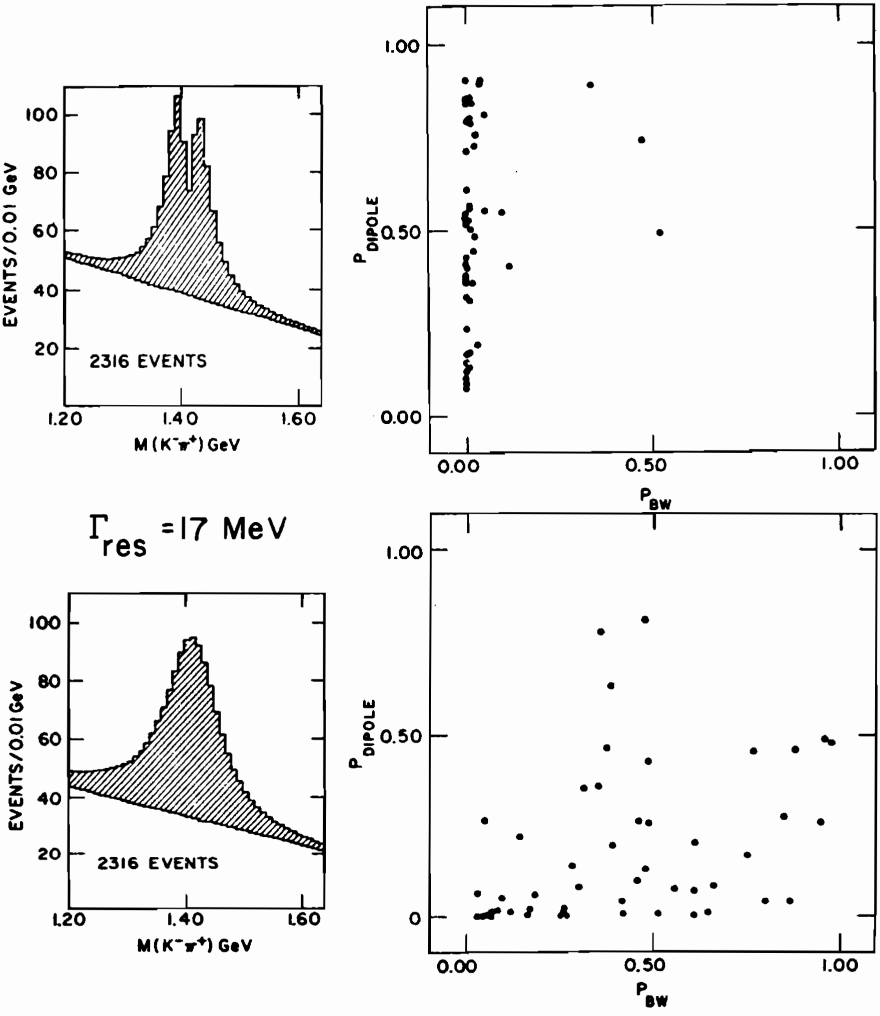

Fig. 44. χ^2 probabilities for Breit-Wigner and dipole fits to each of 50 Monte Carlo experiments are shown in the scatter plots for two assumptions concerning the true distributions (Aguilar-Benitez 1971).

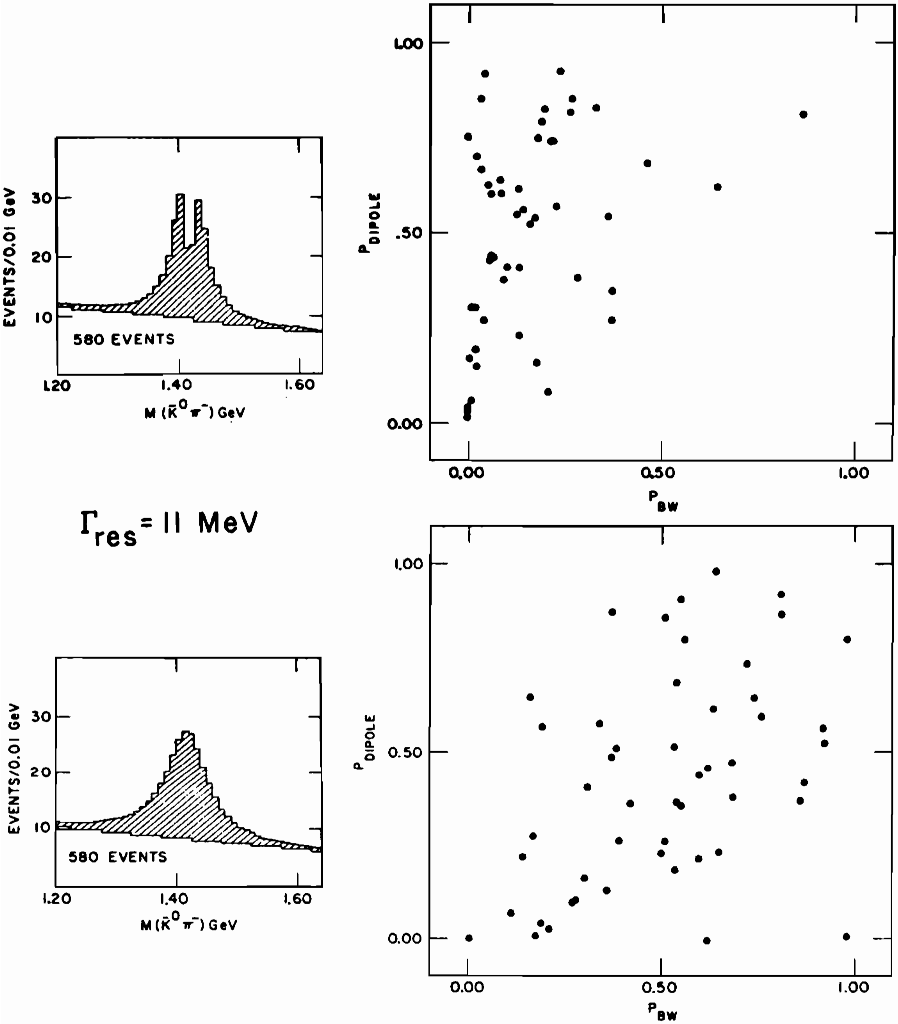

Fig. 45. Monte Carlo results for experiments with 580 events (Aguilar-Benitez 1971).

calculated for a dipole assuming that the true distribution is Breit-Wigner:

$$\Delta\chi^2 = \sum \frac{(\mathrm{BW} - \mathrm{Dipole})^2}{\mathrm{BW} + \mathrm{Background}}$$

Bins of 5 MeV are assumed and the sum is taken from 1200 to 1380 MeV. Gettner gives a relatively simple formula which allows one to quickly calculate $\Delta\chi^2$ for any given experiment:

$$\Delta\chi^2 = \frac{N(A_2)/5\ \mathrm{MeV}}{1 + R} \cdot \frac{\Delta\chi_s^2}{90}$$

where $N(A_2)$ is taken at the peak, R is the background to signal ratio at the peak, and $\Delta\chi_s^2$ is the quantity shown in Fig. 46 as a function of the experimental resolution. For the correct hypothesis, statistical fluctuations will give $\chi^2 = 30 \pm 8$. Gettner suggests that a significant experiment would be one in which $\Delta\chi^2$ is three times the expected fluctuation in χ^2, that is $\Delta\chi^2 \gtrsim 24$. The two distributions used for the Monte Carlo studies of Figs. 44 and 45 have $\Delta\chi^2 = 18$ and 9, respectively; as we saw, the second distribution is clearly unreliable.

Values of $\Delta\chi^2$ for the more significant A_2 experiments are plotted in Fig. 47 as a function of the background to signal ratio. Although Gettner's method does allow for deterioration in statistical significance caused by background, there is an additional systematic uncertainty and experiments with low background should be somewhat preferred. The figure shows that the experiments with structure (open circles) all have relatively low a priori significance.

CERN Reanalyses

Two reanalyses of the Jacobian peak data have been recently performed, the first by Damgaard, Lechanoine and Martin (1972), and the second by Kienzle (1972a). Both groups have produced thick, detailed internal memos. They agree that several improvements can be made in the analysis; for example, one should not use the 1965 runs which apparently differed in mass scale by 25 MeV. They therefore consider only the 1967 runs. They also agree that events in the last part of the run (the beam was retuned) should not be rejected, nor should one reject on the basis of multiplicity. Nor should one reject data in range interval 5, originally thought to have poorer resolution but now found to be similar to ranges 3 and 4, as shown in Table 4. There are differences between the two analyses, as illustrated by the table where the resolution estimated by the two groups differs by 20%.

Damgaard et al. checked for uniformity of events in the planes of the spark chambers. Although they did find small dead spots, both groups agree that this was probably not the cause of structure in the mass distribution.

The conclusion is that structure remains in ranges 3 through 5 ($-t = .21$ to $.29\ \mathrm{GeV}^2$). The significance is estimated to be 3 or 4 standard deviations with a Breit-Wigner fit giving probabilities of 2 to 4%. Fig. 48 shows mass distributions for different range intervals obtained by Kienzle. Note the difference in shape in going from range 2 to range 3; the difference between these spectra is estimated to be 2.7 standard deviations in the dip region. But unless one is willing to postulate a very rapid variation as $\langle t \rangle$ changes from .204 to .227 GeV^2, this effect must be attributed to statistical fluctuations.

The conclusion of these analyses is that the CERN data do still show some evidence for

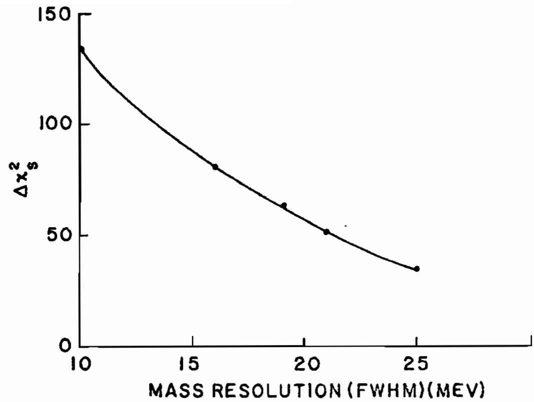

Fig. 46. Parameter used to calculate the a priori ability of experiments to distinguish structure (Gettner 1972).

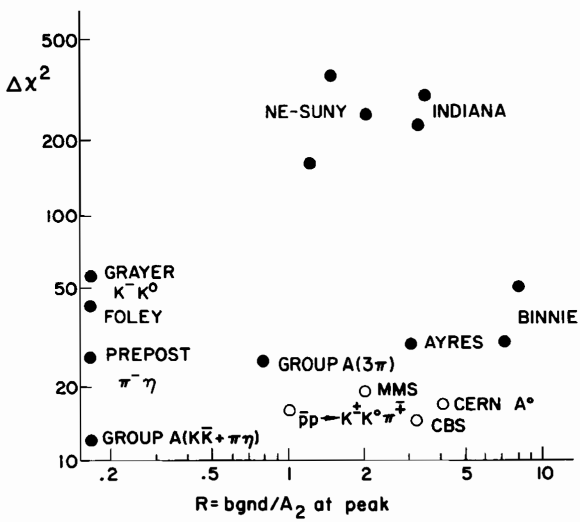

Fig. 47. Summary of a priori statistical significance of A_2 experiments with solid points for those with smooth distributions and open points for structure.

Table 4. Estimates of Missing Mass Resolution (FWHM) for the Five Range Bins of the CERN MMS.

Range	1	2	3	4	5
Chikovani (1967)	28	22	16	18	27
Kienzle (1972b)	22	20	18	18	18
Damgaard, Lechanoine and Martin (1972)	27	24	23	22	22

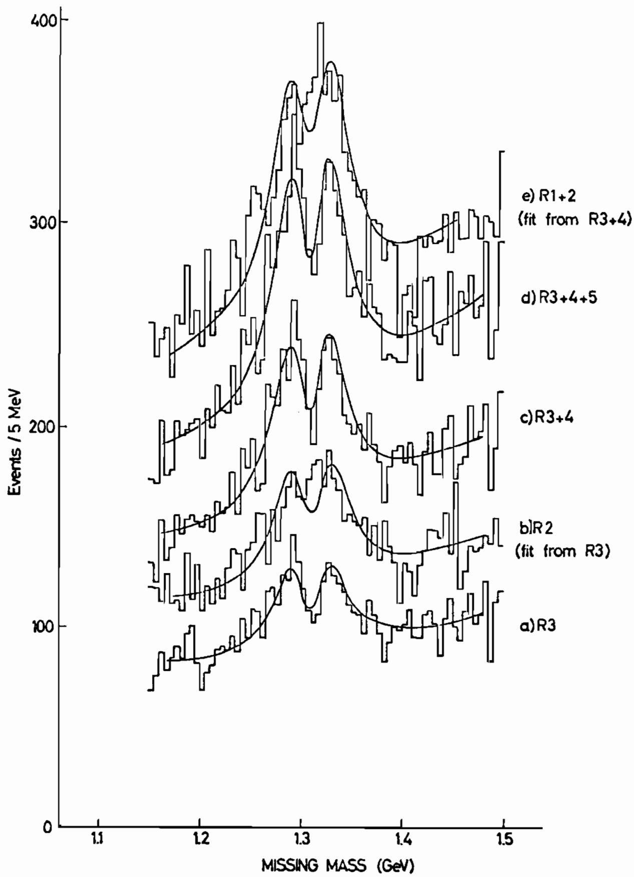

Fig. 48. Results from reanalysis of the 1967 CERN MMS data; the 5 range bins (R1 to R5) for the recoil proton correspond to -t from .18 to .28 GeV^2 (Kienzle (1972a).

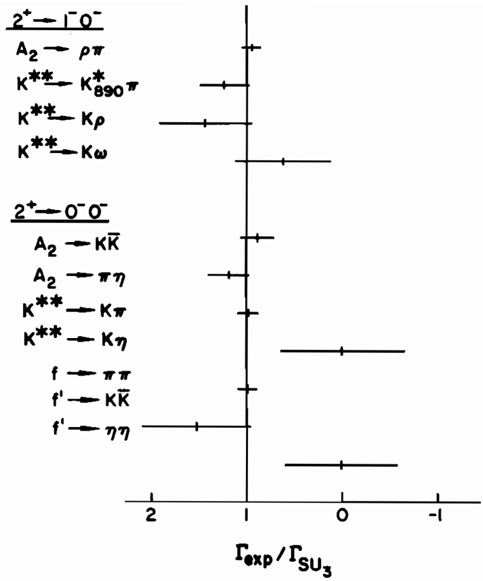

Fig. 49. Comparison of experimental to SU_3 decay widths for the 2^+ nonet (Aguilar-Benitez 1971).

structure, but not as significant as originally stated.

A_2 Conclusions

1) The A_2 is not a dipole.

2) Two interfering Breit-Wigners would help reconcile several experiments. However, the most significant dip experiment (CERN MMS) has been reanalyzed and the structure found to be only 3 or 4 standard deviations; further, this experiment has been directly contradicted by another with much higher statistics. There are several experiments with medium statistics which show structure, but one expects statistical fluctuations to give some results of this type. The high statistics experiments all show smooth distributions. Thus, there is no real need for a second resonance.

3) The simplest and most likely solution is that the A_2 is an ordinary Breit-Wigner. This solution makes good again SU_3 and quark model predictions; for example, the experimental decay widths for the 2^+ nonet are shown in Fig. 49 (Aguilar-Benitez 1971) relative to the values obtained from an SU_3 fit.

R Region

The Regge recurrence of the vector nonet is expected at about 1700 MeV with $J^{PC} = 3^{--}$, and the quark model also predicts such a nonet (triplet D). Indeed, evidence for this nonet has been developing over the past two or three years and is summarized by Graham and Yoon (1972). The prospective members of the nonet are:

$$g(1670) \to \pi\pi, \rho\rho, \pi\omega$$
$$\omega(1680) \to \pi\rho$$
$$K^*(1760) \to K\pi, K\pi\pi$$
$$\phi(1820) \quad \text{(tentative)}$$

Of these only the g has well-determined quantum numbers; the $K^*(1760)$ and $\phi(1820)$ do not even occupy official places in The Table as yet. Using the better known decay modes of these resonances, Graham and Yoon give SU_3 predictions for the other partial widths. A discussion of this nonet is also given by Bramón and Greco (1972b).

It will take some time yet to positively identify the 3^- nonet, much less test the SU_3 predictions. The backgrounds tend to be large at these high masses, and the resonances are getting closer together and harder to untangle from one another. For example, the quark model predicts three nonets in the region 1600 to 1800 MeV, 3^{--}, 2^{-+} and 2^{++} (see, for example, Gilman 1972). The constant spacing in M^2 found in theoretical models for mesons on the leading trajectory leads to a spacing in M proportional to 1/M. Chan and Tsou (1971) have predicted

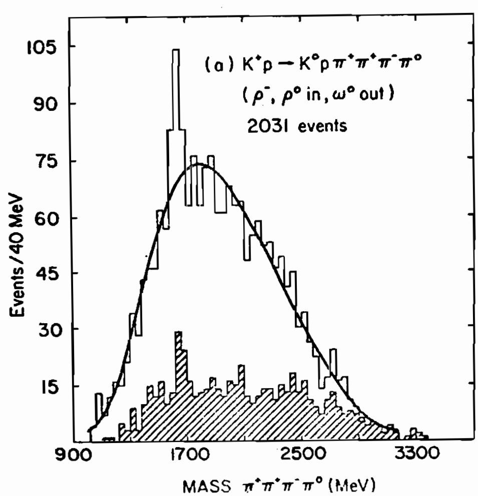

Fig. 50. Compilation of 4π mass spectra at 13 GeV/c (shaded histogram, Holmes 1972) and 10 GeV/c (Barnham 1970); the curve is a polynomial fit to the combined data.

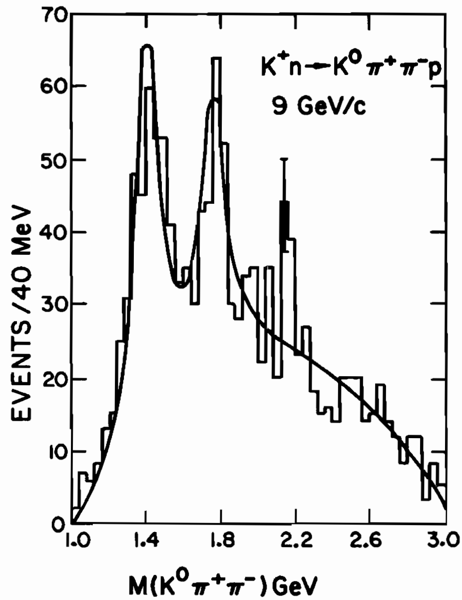

Fig. 51. Mass spectrum for $K^o\pi^+\pi^-$ (Carmony 1971).

in a Veneziano framework that these resonance widths fall slightly faster than 1/M in which case the high mass states would be no more entangled than low mass states. Unfortunately the widths seem not to follow this prediction, and there is the additional complication of broad daughters lying under the high-spin states of the leading trajectory.

There may also be other resonances in this region. Fig. 50 shows a compilation of $K^+p \to K^op\pi^+\pi^-\pi^+\pi^o$ data at 13 GeV/c from Rochester (Holmes 1972) and 10 GeV/c from a Birmingham-Glasglow Collaboration (Barnham 1970). A bump in the four-pion mass distribution is seen at 1630 ± 15 MeV with a width of 130 MeV, four or five-standard deviations above the polynomial curve. One might suppose that this is a manifestation of the g(1670), but the mass is low and no ππ decay is found (contrary to the 40% branching ratio of the g). Other high energy K^+p data exists and the Rochester group suggests that a larger compilation be made.

As was discussed in the K^* section, the $K^-\pi^+$ mass distribution shows a broad enhancement beginning at about 1700 MeV. This enhancement is presumably the sum over several K^* resonances and may be difficult to disentangle, especially since a large amount of background (daughters?) appears to be present. A narrower distribution is seen by Carmony (1971) at 9 GeV/c, Fig. 51, for the reaction $K^+n \to K^o\pi^+\pi^-p$. Here the $K^*(1760)$ appears with a width of about 120 MeV and a height comparable to that of the $K^*(1420)$. One might have expected the Kπ system to appear simpler since it can have only natural spin parity, but just the reverse appears

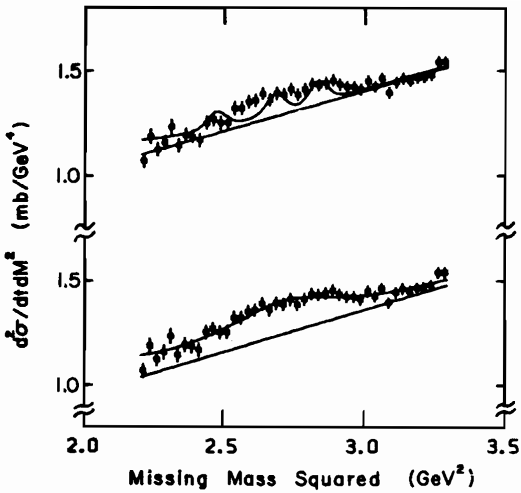

Fig. 52. Missing mass spectrum at 8 GeV/c in the R region, fit to the CERN MMS split-R hypothesis with three zero-width peaks and to a single Breit-Wigner (Bowen 1972).

to be true. It seems likely that careful spin-parity analyses of both $K\pi$ and $K\pi\pi$ will be necessary to understand this region.

The CERN missing mass spectrometer experiment found several narrow bumps in the 1700-MeV region which they labelled R_1, R_2, R_3 (Dubal 1967). Subsequent bubble chamber experiments, however, have found only broad effects such as the g, ρ, and A_3. The Northeastern-Stony Brook Group has looked at the missing mass distribution in the R region at 8 GeV/c, Fig. 52 (Bowen 1972). With a resolution of 22 MeV FWHM, compared with the CERN value of 31 MeV, they collected about six times as many events above background. No evidence for narrow structure was found, only a broad bump with mass 1650 and width 140 ± 30 MeV, presumably some combination of g and A_3.

The Land of STUX

Missing-Mass Results

The Northeastern-Stony Brook Group has collected data at high mass, the spectrum obtained at 13.4 GeV/c being shown in Fig. 53 (Bowen 1972). The computer drawn bumps show the structure expected on the basis of published CERN missing mass spectrometer cross sections (Focacci 1966, Chikovani 1966). Kienzle (1972b) has recently revised these cross sections downward by a factor of 4 ± 1. (The original cross sections were based on the hypothesis that every trigger was a good event, with some system misfunction preventing a large fraction of the events

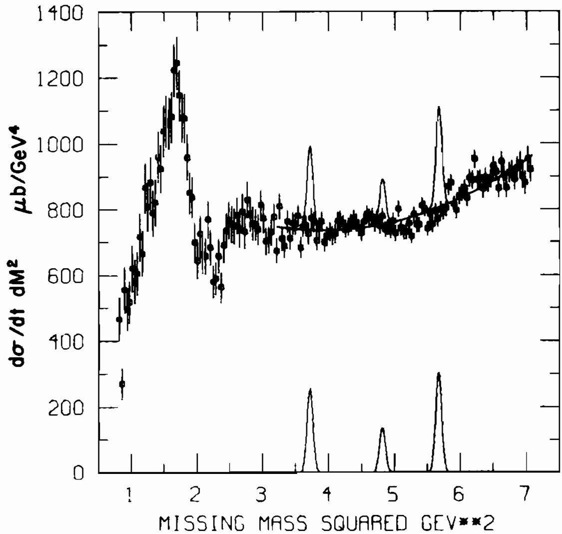

Fig. 53. Missing mass spectrum for $\pi^- p \to pX^-$ at 13.4 GeV/c and $-t = 0.2$ to 0.3 GeV^2 (Bowen 1972). The peaks show the results expected from the published CERN cross sections for the S, T and U (Focacci 1966).

from being reconstructed; more recent experience indicated that these events were accidental triggers.) In any case, the Northeastern-Stony Brook data do not display any significant narrow structure. Fig. 54 summarizes their results as a function of beam momentum; averaging these results gives cross sections generally compatible with zero.

High energy data from Serpukhov were obtained by the CERN-Serpukhov Boson Spectrometer, Fig. 55 (Antipov 1972b). With a mass resolution of 40 and 60 MeV FWHM for incident momenta of 25 and 40 GeV/c, respectively, they find no narrow structure with an upper limit of 3 $\mu b/GeV^2$ at $-t = .26\ GeV^2$.

Bubble Chamber Results

Bubble chamber data from Hawaii (Wohlmut 1972) on the reactions

$$\pi^- p \to X^- p$$
$$\to X^- \pi^0 p$$

at 12 GeV/c were presented to the conference. The resolution of ± 10 MeV is better than the CERN spectrometer above $M_x = 2$ GeV. The data are split into various topologies and a search made for structure. An example of their work is the $\pi^-(\geq 2\pi^0)$ distribution shown in Fig. 56. The curves suggest a small enhancement in the R region (A_3?), and an effect at 2430 MeV with a width of 50 ± 15 MeV. This mass is some 50 MeV lower than the U mass seen by the CERN missing mass spectrometer (2382 ± 24 MeV). The significance of such bumps depends crucially

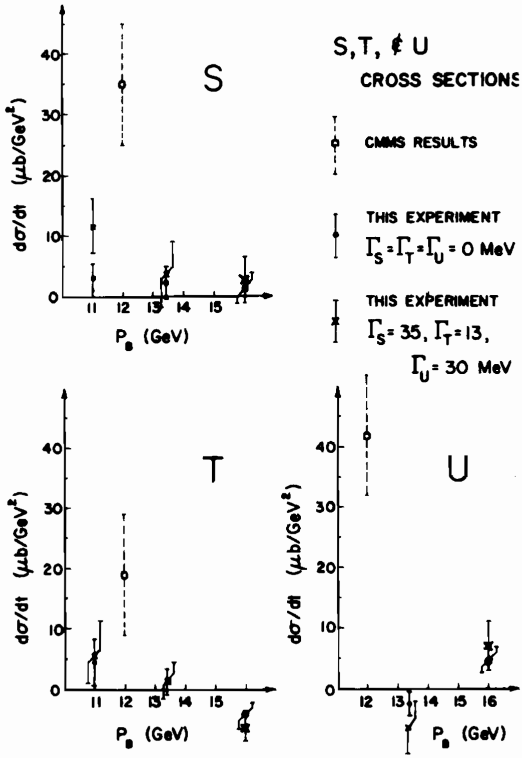

Fig. 54. Cross sections obtained for the S, T and U, averaged over $-t = 0.2$ to 0.3 GeV^2 ("this experiment," Bowen 1972), 0.22 to 0.36 GeV^2 for S and T from the CERN MMS, and 0.28 to 0.36 GeV^2 for the CERN U (Focacci 1966).

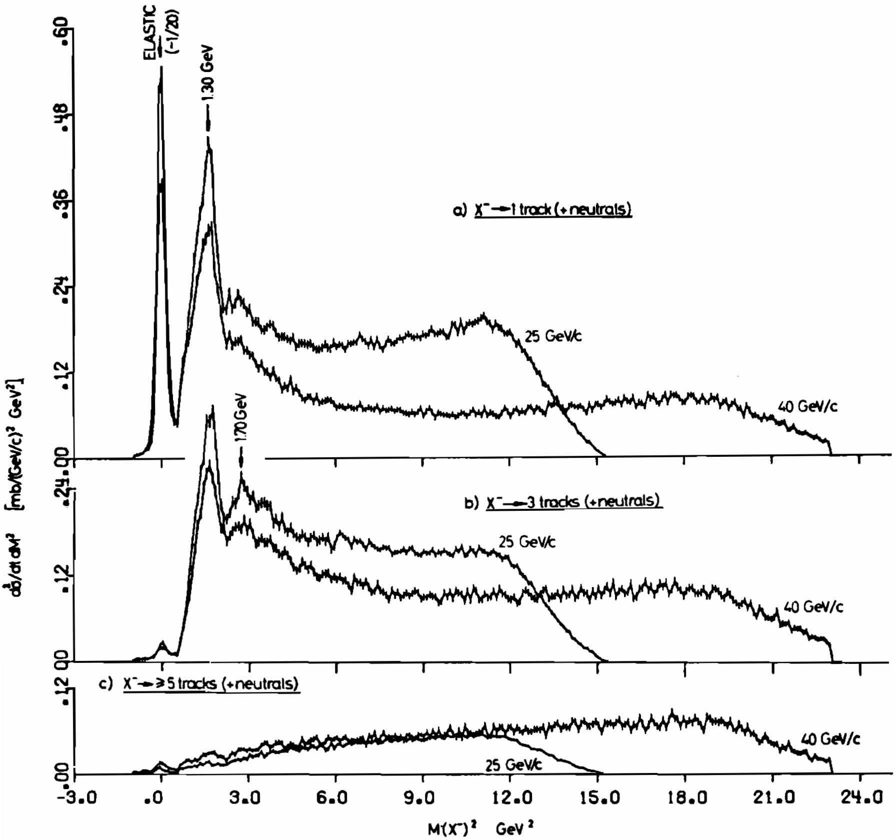

Fig. 55. Missing mass spectra (0.10 GeV^2 bins) for $\pi^- p \rightarrow pX^-$ at 25 and 40 GeV/c, $-t = 0.17$ to 0.35 GeV^2 (Antipov 1972b).

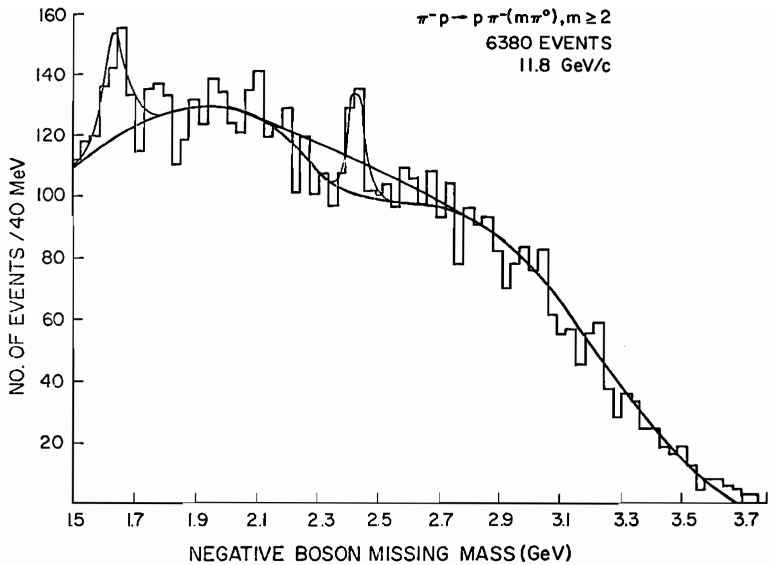

Fig. 56. Mass spectrum for $\pi^-(m\pi^0)$ with $m \geq 2$ (Wohlmut 1972).

on the background assumed; if one uses the straight line background, which I have drawn in the figure, the significance is reduced from 4 to 2.6 standard deviations. With their high statistics, this group should have been able to observe the CERN S, T and U.

As we shall see in the next section, searches for narrow S, T and U mesons have also been made in $\bar{p}p$ annihilation experiments with no obvious success. Combining this with the results of the Northeastern-Stony Brook and Hawaii experiments, it seems likely that the narrow effects were spurious.

Formation Experiments

Experiments of the type $\bar{p}p \to$ Meson have been used extensively to search for mesons above $\bar{p}p$ threshold. This technique has the disadvantage that the angular momentum barrier (von Hippel and Quigg 1972) may suppress mesons with high spin such as those on the leading trajectory. If the effective interaction radius were about 1 fermi, a factor of five suppression would be expected, while a radius of half this value would lead to a suppression one hundred times greater. Daughters with lower spin will not suffer such a large suppression and may thus be enhanced relative to the leading trajectory, especially near $\bar{p}p$ threshold.

There are several advantages of formation experiments:

1) No baryon cluttering up the final state;

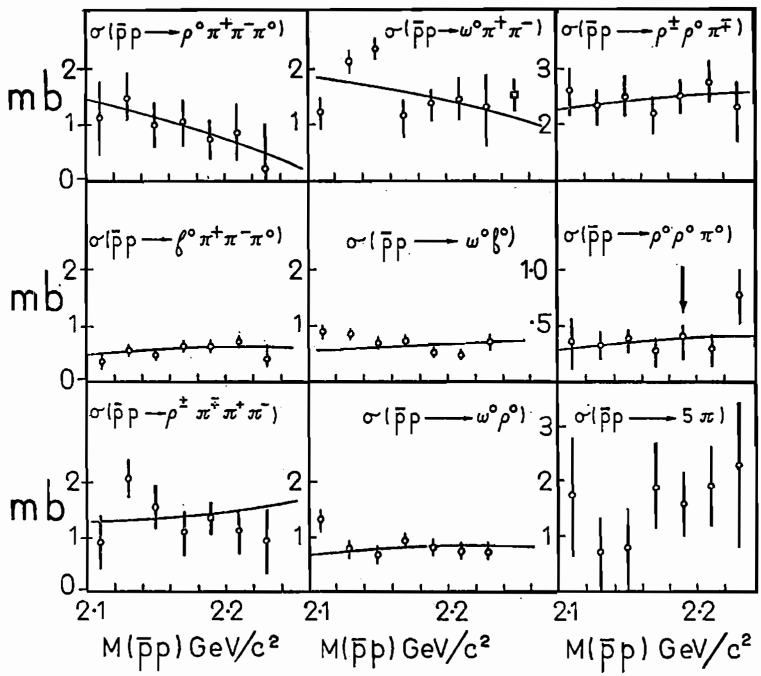

Fig. 57. Five-pion final states from $\bar{p}p$ annihilation in the T region (Donald 1972b).

2) no Deck-type mechanism;

3) good mass resolution.

There are also some disadvantages:

1) Only one $M_{\bar{p}p}$ value can be studied at a time, and there may be normalization problems from run to run;

2) a large number of amplitudes seem to be present (e.g., Fields 1971).

Over the years, many narrow effects have been reported, but none have been convincingly confirmed and many have gone away. For example, there were reports of $K\bar{K}\omega$ enhancements in both the T and U regions (Montanet 1969, Chapman 1971); with more statistics these effects have gone away (Donald 1972a, Oh 1972). An enhancement of 0.4 ± 0.1 mb in the $\rho^o\rho^o\pi$ channel was found three years ago at 2190 MeV (Kalbfleisch 1969). A high statistics experiment reported to this conference by a Liverpool-Paris Collaboration (Donald 1972b) considered five-pion final

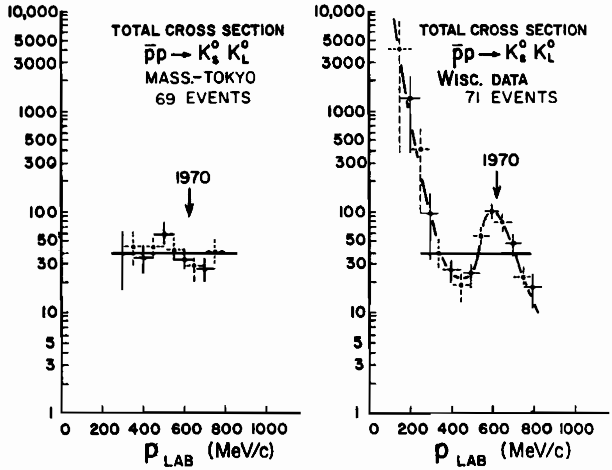

Fig. 58. Comparison of the $\bar{p}p \to K_S^o K_L^o$ results of the Massachusetts-Tokyo Collaboration (Carson 1972) and Wisconsin (Benvenuti 1971).

states in the T region; as shown in Fig. 57 they found no $\rho^o \rho^o \pi^o$ bump at 2190. The other distributions shown in the figure also appear to be smooth with the possible exception of the $\omega\pi^+\pi^-$ final state with two high points near 2140.

$\bar{p}p \to K_S^o K_L^o$

One of the more startling contradictions between experiments is shown in Fig. 58 for the process $\bar{p}p \to K_S^o K_L^o$. The Wisconsin results (Benvenuti 1971) are based on 71 events; the data are double binned, resulting in twice the number of points and a very smooth appearance to the distribution. The Wisconsin data showed a 35 MeV wide bump at a mass of 1968 MeV. The final state restricts the quantum numbers to odd spin with C = P = -; the data were found consistent with the simplest assumption, J = 1. New experimental data were reported to this conference by a University of Massachusetts-Tokyo Collaboration (Carson 1972). With 69 events, this experiment has statistics similar to Wisconsin, but the results shown in Fig. 58 are quite flat. The authors reach the conclusion that they "do not see any clear evidence for a resonant state." While the difference might be attributed to the low statistics involved, a fluctuation of perhaps four standard deviations, systematic effects are also possible. In particular, it is non-trivial to determine the effective path length of the incident beam as a function of momentum because of the rapid slowing of low momentum antiprotons.

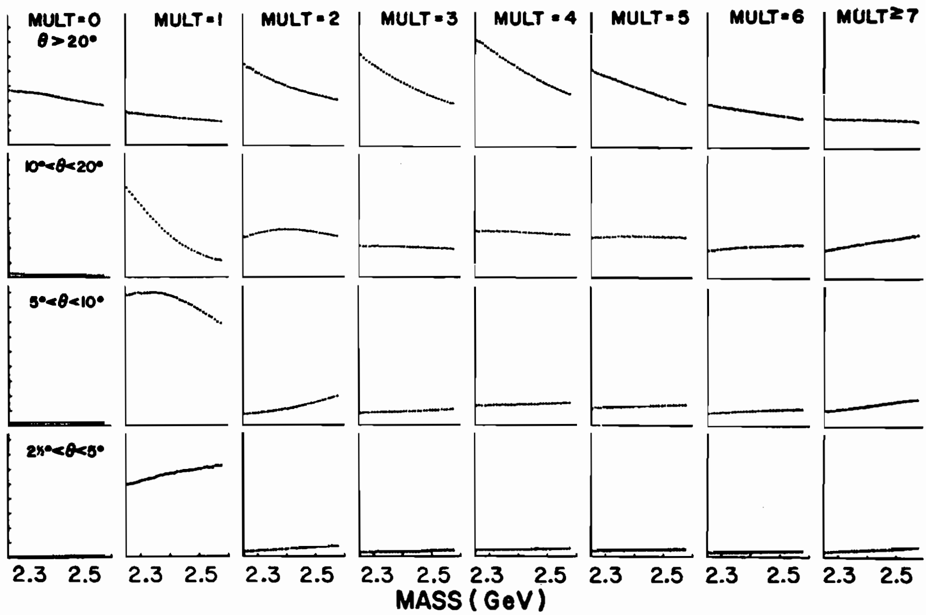

Fig. 59. Subsets of the RAS data in the U region (K. J. Cohen 1972).

<u>Rutgers Annihilation Spectrometer</u>

The Rutgers Annihilation Spectrometer (RAS) at Brookhaven has taken data in the T and U regions (K. J. Cohen 1972, Alspector 1972). This is a pure counter experiment with no spark chambers, allowing an accumulation of a very large number of events, more than 10^8. They vary the mass by changing the beam momentum and obtain a mass resolution at 2 GeV of about ± 5 MeV.

Fig. 59 shows the data obtained in the U region (K. J. Cohen 1972) for different values of peripherality and multiplicity. Forward scintillation counters measure peripherality, defined as the laboratory angle of the charged particle closest to the direction of the incident beam. Multiplicity, the number of charged particles coming from a reaction is measured by an array of 32 counters and should be even. However, three effects make the multiplicity measurement somewhat uncertain:

1) two tracks may pass through the same counter;
2) slow particles such as the recoil proton from elastic scattering stop in the target, and
3) gamma rays may convert in the target or surrounding material.

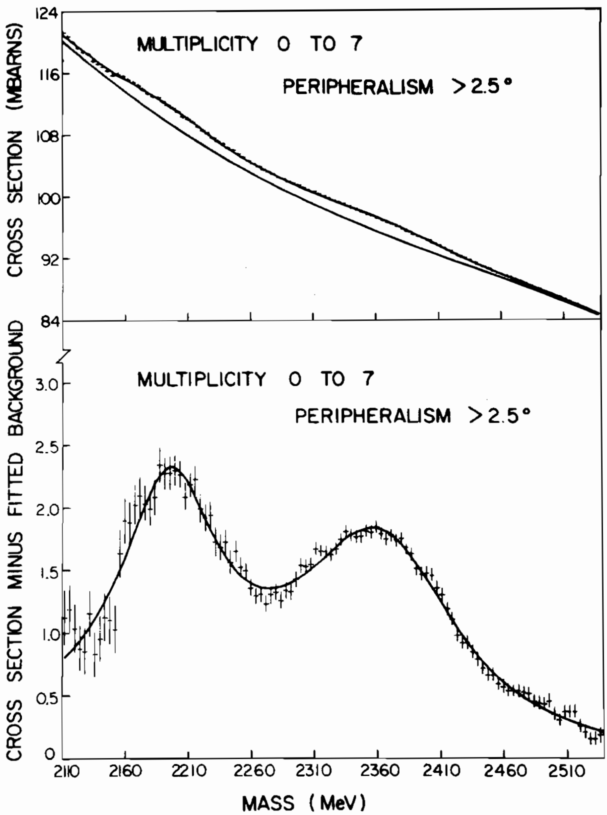

Fig. 60. Combined RAS data, before and after subtraction of third order polynomial background (K. J. Cohen 1972).

Table 5. Parameters Found for the T and U Bumps.

	"T" M MeV	"T" Γ MeV	"T" σ mb	"U" M MeV	"U" Γ MeV	"U" σ mb
CERN MMS	2195 ± 15	$\leqslant$15		2382 ± 24	$\leqslant$30	
ABRAMS*	2187 ± 3	56 ± 8	1.85 ± .1	2363 ± 2	172 ± 10	2.52 ± .1
RAS	2195 ± 5	95 ± 15	2.25 ± .08	2360 ± 5	163 ± 15	2.0 ± .07

*Results from fit by RAS Group

Although the RAS results do not exhibit any narrow structure, the wide Abrams (1970) bumps are verified. The data in Fig. 60 nearly represent the total cross section (events with charged particles less than 2.5° are excluded). The authors find that the data cannot be fit with a smooth curve, but two bumps sitting on top of a third order polynomial in the mass do fit well. The bumps are only 2 mb out of a total of about 100 mb. With this much background, it is clear that the heights and widths of the bumps depend critically on the exact form assumed for the background.

The bump parameters for the new data are shown in Table 5; the RAS Group has also refit the Abrams data with results shown in the table. The agreement between the two sets of data is fairly good, although the Abrams T bump is somewhat narrower and the cross sections agree only to within about 20%. Also shown in Table 5 are the results from the CERN Missing Mass Spectrometer (Focacci 1966); the masses for T and U are in reasonable agreement with the Abrams and RAS bumps, but the widths are more than a factor of 5 narrower.

The RAS group finds that the positions and widths of the bumps do not vary significantly with multiplicity and peripheralism. One might have hoped that the T and U bumps would be enhanced in the nonperipheral data. Fig. 61 (Alspector 1972) shows that the signal to background ratio is relatively independent of the peripheralism cut, however, and the T and U bumps are both spread out over many multiplicities. The only noteworthy structure in the multiplicity distribution is the lack of a T signal in multiplicity zero and two. This may be an indication that the T bump comes mainly from annihilation into several particles plus some elastic scattering, but not single pion production $\bar{p}p \rightarrow N\bar{N}\pi$. The latter point agrees with bubble chamber analyses (e.g., Cooper 1968, Donald 1972c).

Bubble chamber data contributed to this conference (Donald 1972c) indicate that some of the U bump is due to single pion production as well as four and six pion annihilation (Eastman 1972). It seems likely that this region is complicated with structure coming possibly from several broad resonances, as for the R; in particular, Abrams (1970) found both I = 0 and 1 structure in the U region.

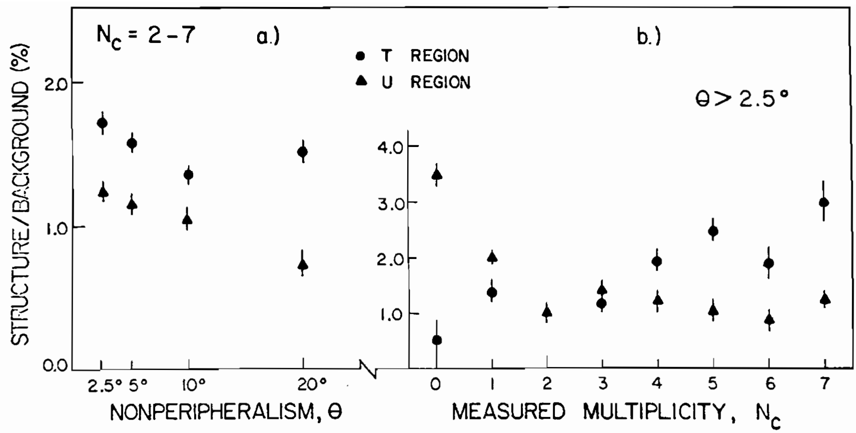

Fig. 61. RAS signal to background ratios as a function of the angle of the most forward charged particle and the multiplicity (Alspector 1972).

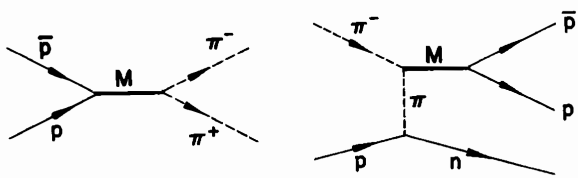

Fig. 62. Diagrams for $\bar{p}p \leftrightarrow \pi^-\pi^+$.

<u>$\bar{p}p \leftrightarrow \pi^+\pi^-$</u>

The reaction $\bar{p}p \rightarrow \pi^-\pi^+$ is limited to triplet $\bar{p}p$ states with G = +1; spin parity is related to isotopic spin:

$$I = 0 \quad J^{PC} = 0^{++}, 2^{++} \ldots$$
$$I = 1 \quad J^{PC} = 1^{--}, 3^{--} \ldots$$

With this relatively small number of amplitudes, there is a good chance that one may eventually understand the reaction.

While the $\bar{p}p$ initial state formation experiment is straightforward, the inverse reaction can be studied as $\pi\pi$ inelastic scattering with the extrapolation to the pion pole indicated in Fig. 62. While this method has the usual difficulties associated with extrapolation to the pole, it also has certain advantages: the pp threshold region can be observed and normalization is simpler since data at all $M_{\bar{p}p}$ are collected simultaneously.

The reaction $\bar{p}p \rightarrow \pi^-\pi^+$ has been studied in a series of experiments at Brookhaven by a

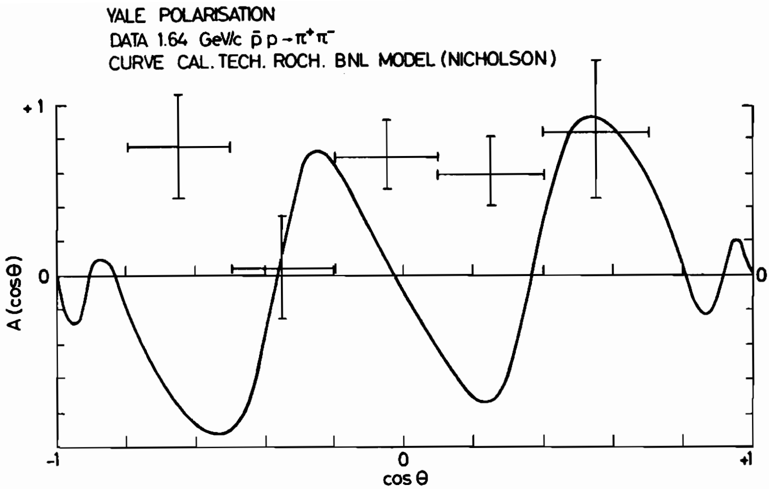

Fig. 63. Comparison of Yale polarization (Ehrlich 1972) with model proposed by Nicholson (1969) (figure taken from Astbury 1972).

Caltech-Rochester-Brookhaven Collaboration (Nicholson 1969, 1972). They found considerable structure in the angular distribution and suggested that interference between two resonances with J = 3 and 5 could explain the large amount of $Y_8(\cos\theta)$ required to fit the data. Fig. 63 shows the asymmetry from a polarized target obtained by a Yale group (Ehrlich 1972) for this reaction. Although the data are somewhat meager, the Nicholson (1969) model is clearly rejected. The reaction is also being studied in detail by a counter experiment at CERN (Astbury 1972).

The inverse reaction has been recently observed by two spark chamber experiments. Fig. 64 shows some of our 6-GeV/c Argonne data (Ayres 1972). The signature for the reaction of interest has some background, and the data shown in Fig. 64 have been corrected by a side-band subtraction. There appears to be little evidence for narrow structure even though the mass resolution is typically 8 MeV FWHM.

Data obtained by the CERN-Munich Collaboration at 19 GeV/c are shown in Fig. 65 (Grayer 1972b). Several tests indicate OPE dominance. Extrapolation of the data to the pion pole (Dürr-Pilkuhn form factor) gives good agreement with the direct measurements of the inverse reaction, as shown in Fig. 66. The t distributions are well fit by the OPE curves, and the Treiman-Yang angular distribution is rather flat as expected for one pion exchange. Fig. 67 compares the angular distributions observed in bubble chambers for the direct reaction with those found for the inverse reaction. The data are in qualitative agreement, and the lack of quantitative agreement may be due to differences in averaging over $M_{p\bar{p}}$. These angular

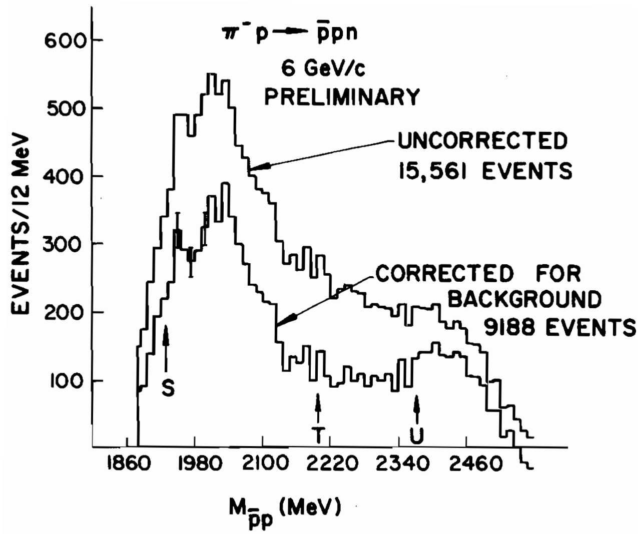

Fig. 64. Spectrum of $\bar{p}p$ effective mass at 6 GeV/c uncorrected for acceptance (Ayres 1972).

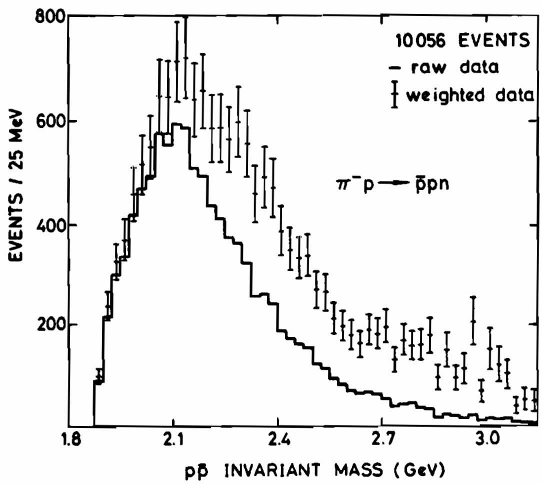

Fig. 65. Spectrum of $\bar{p}p$ effective mass at 19 GeV/c (Grayer 1972b).

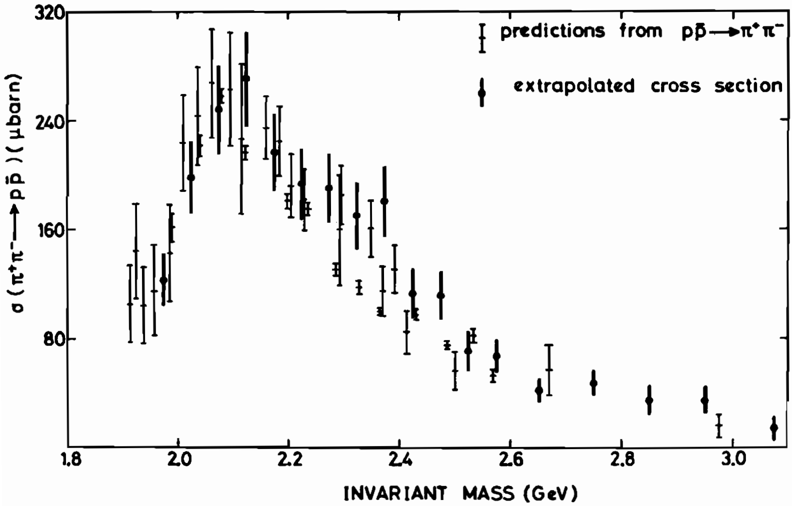

Fig. 66. Comparison of $\bar{p}p \rightarrow \pi^-\pi^+$ and the 19-GeV/c data for $\pi^-p \rightarrow \bar{p}pn$ extrapolated to the pion pole (Grayer 1972b).

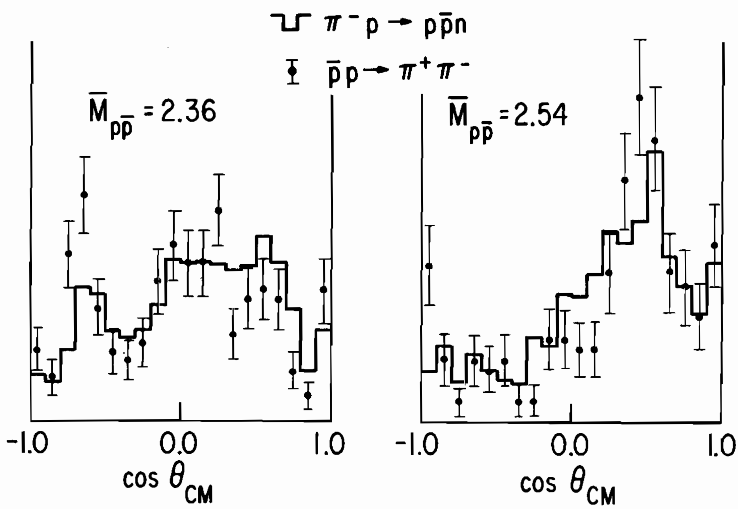

Fig. 67. Comparison of the angular distributions for $\pi^-p \rightarrow \bar{p}pn$ (Grayer 1972b) and $\bar{p}p \rightarrow \pi^-\pi^+$ (Campbell 1972 and Fields 1972).

distributions appear to be very rich and deserving of more detailed analyses.

$\bar{p}p$ Summary

We quote the conclusions given by Fields in the parallel session:

1) No narrow resonances have been confirmed.
2) The broad Abrams bumps have been confirmed.
3) The T(2190) is not $N\bar{N}\pi$; the U(2360) may be partially $N\bar{N}\pi$.
4) $\pi\pi$ and $\bar{K}K$ final states show promise of being tractable.
5) The bubble chamber technique has already been pushed close to its practical limit.

Several excellent reviews of formation experiments can be found in the proceedings of the Symposium on $N\bar{N}$ Annihilations held at Chexbres (CERN Report 72-10, edited by Montanet).

Exotics

At the moment there appear to be no good candidates for exotic mesons. Many mass spectra with charge 2 or strangeness 2 are examined every year. Taken individually these results are not so interesting and people don't bother to publish them. Taken together, however, one might be able to set significant upper limits (or even find an exotic bump). Compilations of exotic bubble chamber channels should be made and the results published. High statistics spectrometer experiments should also be analyzed for exotic production, especially in the backward direction where production mechanisms may be more favorable (Freund 1969; Jacob and Weyers 1970).

Searches should also be made for second-class exotics, those mesons (mainly natural spin parity) with wrong C parity for a $q\bar{q}$ system. Some examples of states with explicit C parity are shown in Table 6 together with the exotic spin parity values forbidden in the simple quark model.

Table 6. Examples of Second Class Exotics

C	System	J^P
+	$\pi\eta$, πf, $\rho^o\rho^o$, $\rho\omega$	1^-, 3^-, 5^- ...
-	$\pi^o\rho^o$, $\pi\omega$, $\eta\rho$	0^-; 2^+, 4^+ ...

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