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SOME TOPICS IN BOSON SPECTROSCOPY

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I. INTRODUCTION

Although my report to this Conference was supposed to be concerned with a review of hadron spectroscopy it needs hardly be stressed that I cannot do justice to this subject in my allotted time. Consequently my plan is to discuss a few items which have in recent times been the subject of considerable research activity without claiming either completeness or topical choices of the greatest possible significance. Although the official Conference program stipulates a "Review of Hadron Spectroscopy," I shall totally confine myself to boson spectroscopy. I had anticipated that Dr. Lovelace, originally scheduled to give a companion presentation, might stress the baryons, and I note further that many of the baryon spectroscopists are not here but rather in my home territory of Berkeley having a Conference on Polarized Targets.

My order of presentation is such that I shall first discuss some aspects of various natural-spin parity $[P = (-1)^J]$ nonets, and then briefly comment on some of the diffractively-produced unnatural-spin-parity systems.

II. THE 2^+ NONET

As you undoubtedly all know, the possible existence of the fine structure in members of the tensor nonet has been a subject of very considerable experimental investigation and controversy for some years. In particular, a series of experiments performed by the CERN Missing-Mass-Spectrometer-Boson Spectrometer Group[1-3] showed the isovector member of the tensor nonet, the A_2, with a mass spectrum containing a marked dip at its center. The fact that a nearly identical dip appeared at two different incident momenta, namely 2.6 (Ref. 2) and 6-7 GeV/c (Ref. 1) and further manifested itself in the $K\bar{K}$ decay mode[3] as well as in the three-pion modes initially suggested it to be an intrinsic property of the A_2 which was usefully parametrized by replacing the usual Breit-Wigner form

$$\mathrm{BW} \sim \frac{1}{(M - M_o)^2 + (\Gamma^2/4)} \qquad (1a)$$

with the dipole form,

$$\mathrm{Dipole} \sim \frac{(M - M_o)^2}{[(M - M_o)^2 + (\Gamma^2/4)]^2} \quad . \qquad (1b)$$

It need hardly be pointed out that the establishment of such a remarkable effect goes well beyond simple displays of mass spectra and into detailed discussions of resolution, all of which were provided in the references cited above.

The credibility of the dipole spectrum as an intrinsic property of the A_2 faded about a year and a half ago with the demonstration from the Berkeley bubble chamber experiment of Alston-Garnjost et al.[4] that the A_2^+ (the experiments of Refs. 1-3 were on A_2^-) produced by 7 GeV/c π^+ showed no evidence of dipole structure in any of its three principal decay modes $\rho\pi$, $K\bar{K}$, $\eta\pi$. Shortly thereafter two new studies of the reaction

$$\pi^- p \rightarrow A_2^- p \rightarrow K^- K^o p \ ,$$

one by the BNL group of Foley et al.[5] and the other by the CERN-Munich Group of Grayer et al.[6] at incident momenta of 20 and 17 GeV/c respectively gave mass spectra in strong disagreement with the dipole form (1b), while in satisfactory agreement with the Breit-Wigner form (1a). Attempted reconciliations of these apparently conflicting pieces of data were made by abandoning the notion of the central mass dip as an intrinsic A_2 property, proposing the production of several interfering resonances and taking advantage of the fact that such production characteristics as incident momentum, production angle, sign of beam particle did differ in the various experiments.[7] This loophole, however, has now been shut rather tightly by the recent high-statistics Northeastern-Stony Brook experiment of Bowen et al.[8] which, in one of its runs, practically duplicated the running conditions of the original CERN Missing-Mass Spectrometer run.[1] There seems to be excellent agreement between the two experiments with one fundamental exception, namely the complete absence of the dip at the center of the A_2^- peak in the Northeastern-Stony Brook experiment.

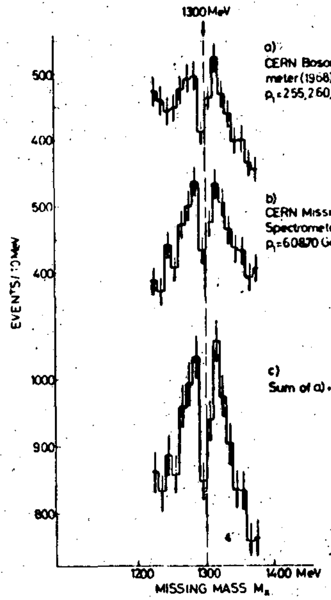
After these somewhat lengthy historical comments, I want to exhibit some of the data. Figure 1 shows both the original CERN data from the Missing-Mass and Boson Spectrometers and the recent Northeastern-Stony Brook results. The statistics of the latter experiment are enormously larger, and the adequacy of their resolution is discussed in their paper[8] to which the interested reader should refer for details. Figure 2 shows the $A_2^- \rightarrow K\bar{K}$ data from the CERN Boson Spectrometer[3] and from the more recent, higher statistics and higher energy experiments of the BNL[5] and CERN-Munich Groups.[6] Finally, in view of the rather different experimental technique, it seems worthwhile to exhibit the results of the most impressive of the bubble chamber experiments even though the statistics are smaller than those of the recent counter experiments. Figure 3a shows the results of the LBL Group A experiment[4] which first cast serious doubt on the dipole structure of the A_2, and Fig. 3b gives a recently published K^oK^- mass spectrum from a bubble chamber experiment by the BNL Group of Crennell et al.[9]

It is rather natural that SU(3) considerations should have suggested a search for dipole structure in members of the 2^+ nonet other than the A_2. The results of such searches for the f(1260) from LBL Group A[10] and for the K*(1420) from Aguilar-Benitez et al. at BNL[11] are shown in Figs. 4 and 5. Again for discussions which show that the resolution is adequate for the result to be meaningful the reader is referred to the papers in question, and it suffices here to say that no indication of dipole structure is seen.

Needless to say, the results which I have shown in these first few figures represent by no means the totality of all experiments which have attempted to say something on the subject. A rather useful summary from which the potential informational content of each A_2 experiment is quickly seen has been made by G. Lynch[12] of LBL by the useful device of defining a continuous variable δ (labeled the duplicity (!)) whose variation from 0 to 1 carries the mass spectrum from a Breit-Wigner shape to a dipole shape.[13] Specifically,

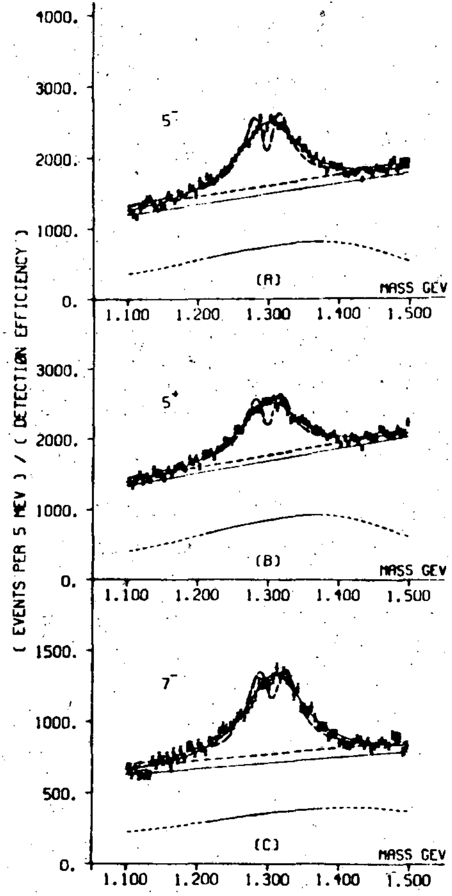
$$\text{Mass Spectrum} = \delta\left[\begin{matrix}\text{Dipole}\\ \text{Shape}\end{matrix}\right] + (1 - \delta)\left[\begin{matrix}\text{B.W.}\\ \text{Shape}\end{matrix}\right] + \text{Background} . \quad (2)$$

The uncertainty in δ depends of course on statistics <u>and</u> mass resolution. Figure 6 shows the results of Lynch's fits to the quoted spectra



Compilation of the total available mass spectrometer data relevant to an A_2 splitting in $\pi^- p \rightarrow pX^-$:
a. Total CERN Boson Spectrometer ("0° method") data. A_2 produced close to threshold (p_1 near 2.6 GeV/c).
b. Total CERN Missing-mass Spectrometer ("Jacobian-peak method") data, A_2 produced far above threshold (p_1 = 6 and 7 GeV/c).
c. Total sum = sample (a) + sample (b).

(a) Ref. 2



Mass spectra from 5 (π^-), 5 (π^+), and 7 (π^-) GeV, respectively. The solid lines through the data are the Breit-Wigner fits, and the solid straight lines beneath the data are the associated fitted linear backgrounds. The dashed lines in the region of the data are the dipole fits (Γ_{dipole} = 28 MeV, fixed) and their associated linear backgrounds. The calculated detection efficiencies versus mass are shown (arbitrary units) as dashed lines (1.10 ≤ M ≤ 1.22 GeV and 1.38 ≤ M ≤ 1.50 GeV) and as solid lines (1.22 ≤ M ≤ 1.38 GeV, "resonance" region). The detection efficiencies have been normalized so that at M = 1.300 GeV the ordinates on the graphs indicate the actual number of events detected in the experiment per 5-MeV bin.

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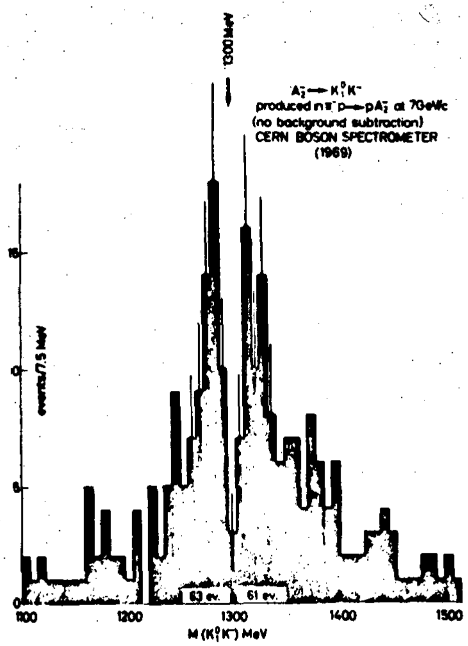
(b) Ref. 8

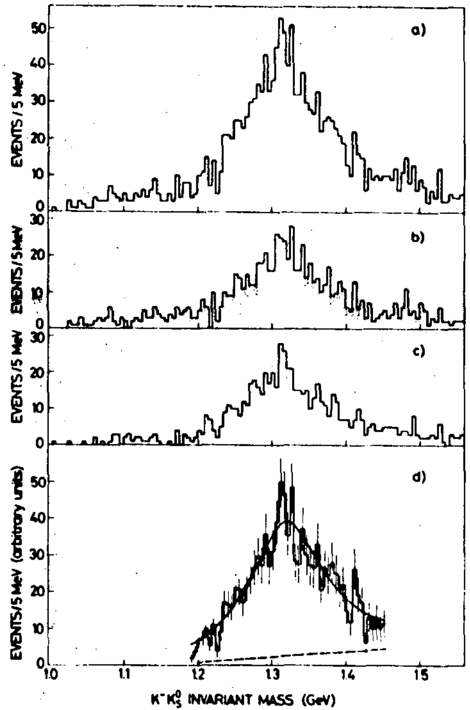
Fig. 1. A_2 mass spectra in reactions $\pi^{\pm} p \rightarrow pX^{\pm}$.



Missing mass spectrum for $A_2^- \rightarrow K_1^0K^-$ events, produced in $\pi^-p \rightarrow pA_2^-$ at $|t| = 0.28$ (GeV/c. The dip is centred at $M = 1300$ (± 5) MeV. Note the low background level in the A_2 region (no background subtraction.

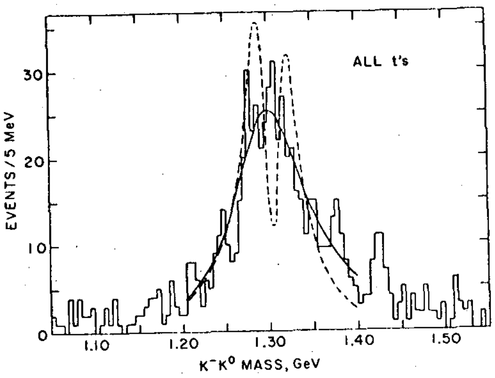
Ref. 3

Fig. 2. K^-K^O mass spectra from $\pi^-p \rightarrow pK^-K^O$.



$K^-K_S^0$ invariant mass: a) all $|t|$, unweighted: b) $|t| < 0.2$, unweighted: c) $0.2 < |t| < 0.7$ $(GeV/c)^2$, unweighted; d) weighted $0.0 < |t| < 0.7$ $(GeV/c)^2$. Full line: Breit-Wigner type fit of the form

Ref. 6



The $K^-K_s{}^0$ effective-mass spectrum for $K^-K_s{}^0$ events with a recoil mass in the region 0.76 to 1.06 GeV. The curves are described in the text.

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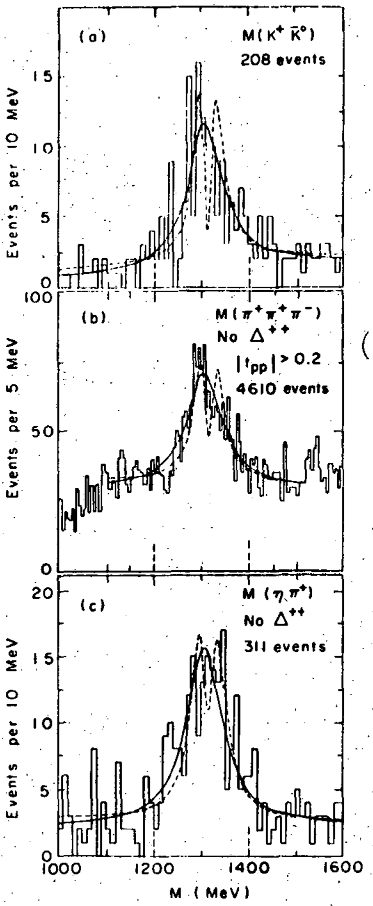
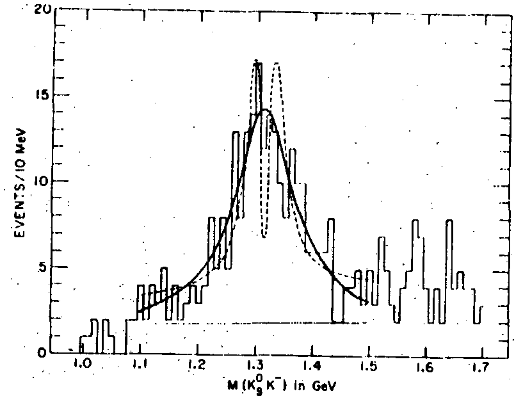
Ref. 5



Mass plots in the A_2 region. The curves are from the likelihood fit to the three decay modes simultaneously: BW (solid line) and DP (dashed line).

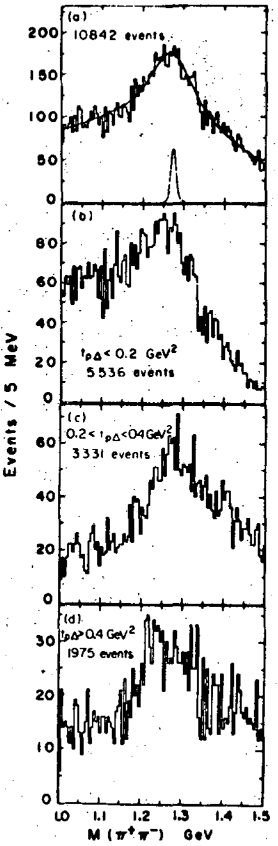
(a) Ref. 4.



(b) Ref. 9.

$K_S^0K^-$ mass with solid curve indicating fit of data to a simple Breit-Wigner fit, solid line the background for that fit; the dotted line indicates the best dipole fit. Excess events in the 1.5 - 1.7 GeV mass region are attributed to the $g(1630)^-$ meson. (See text for details.)

Fig. 3



Mass plots in the f^0 region. A Δ^{++} is always required. The solid curve is a fit with a Breit-Wigner s-wave resonance formula plus a linear background. The dashed curve is our resolution function normalized to 4% of the number of f^0 resonance events found in the fit.

Fig. 4. Ref. 10.

Bubble chamber mass plots.

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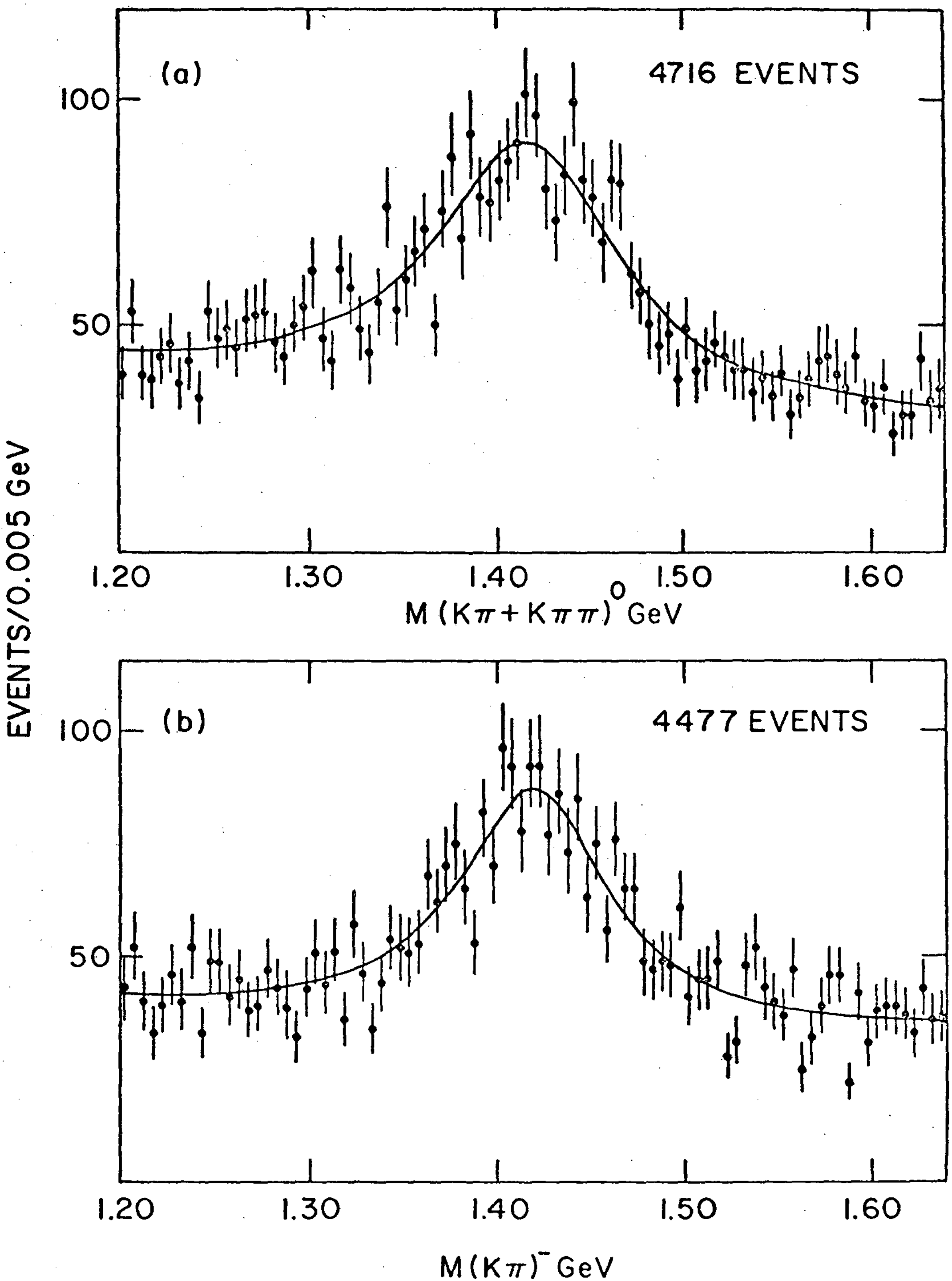

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Fig. 5. K*(1420) mass spectra.[11]

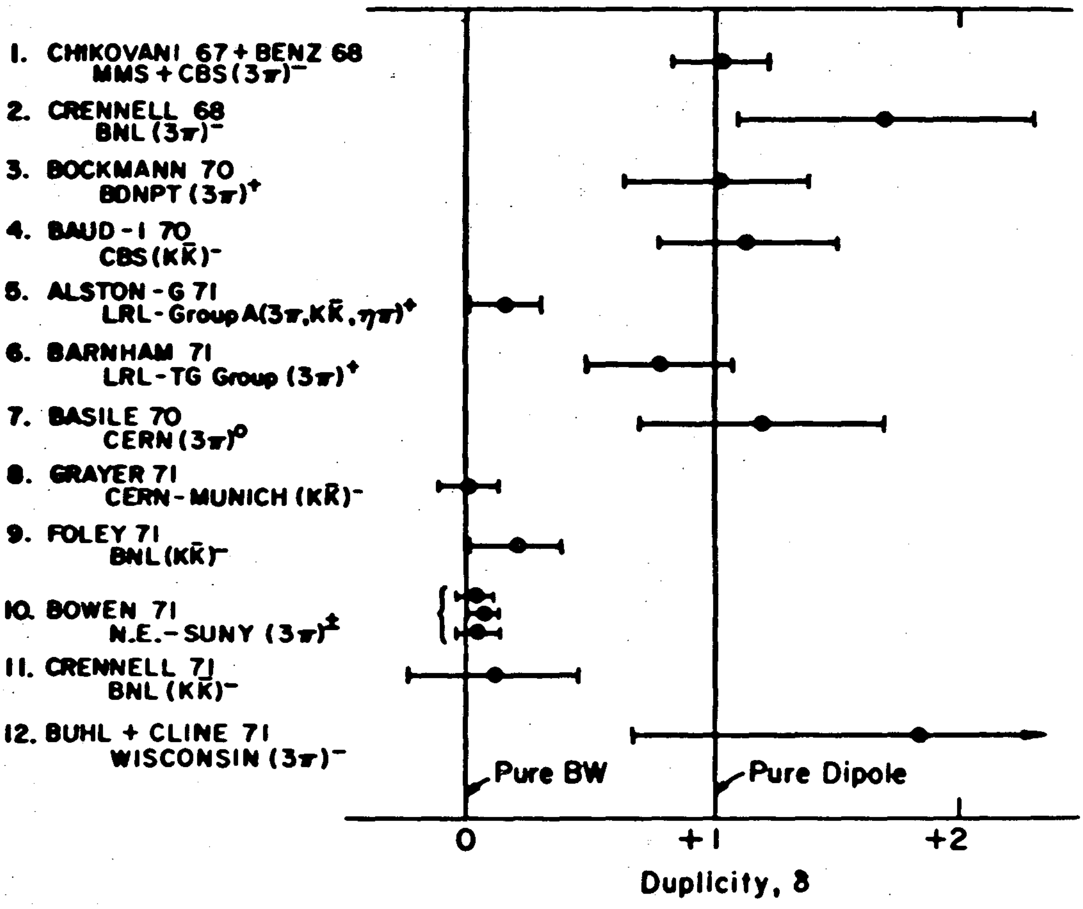

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Fig. 6. Duplicity plot.[12]

from a variety of experiments which include the ones shown in Figs. 1, 2 and 3, as well as several others. If we take the sensible criterion that no experiment has much information content on the fine structure of the A_2 spectrum unless the full error width in δ ($2\sigma_\delta$) is less than 0.5 we see that in fact only the experiments shown in Figs. 1a, 1b, 2b, 2c and 3a had anything really significant to say. Of these only that of Fig. 1a (the original CERN experiments) favors the dipole structure; all others strongly support the Breit-Wigner shape.

Where does this leave us? In my view the notion of the dipole mass spectrum as an intrinsic property of the A_2 or of other members of the 2^+ nonet is conclusively ruled out. The more subtle idea that there may be some variations in A_2 spectrum shape due to neighboring resonances, interference with background, etc. which can vary with incident momentum, beam particle, or production angle is obviously much more difficult to rule out. My own opinion is that there is very little solid evidence for such effects beyond the usual consequences of varying background shapes and reflections from possible isobars.

To bring to a close this discussion of the more controversial aspects of the tensor nonet I simply want to exhibit in Table I the results of a recent SU(3) analysis of the decay modes of the members of this nonet made by Aguilar-Benitez et al.[11] Although this is certainly not the last word on the subject in terms of incorporating all the latest known values of widths, branching ratios, etc. it indicates clearly an excellent fit to SU(3) decay rate predictions, leading to the conclusion that our level of understanding of this nonet is presently in rather satisfactory shape.

III. LOW ENERGY $K\pi$ AND $\pi\pi$ SPECTROSCOPY ($\lesssim$ 1 GeV)

It is well known that our rather extensive knowledge of $S = 0$ and $S = -1$ baryon spectroscopy stems from the ability to do phase-shift analyses from formation experiments rather than rely solely on the results of production experiments. Similar attempts in boson spectroscopy have been based on the study of reactions dominated by the one-pion-exchange mechanism and have particularly focused on the study of the scalar (0^+) $K\pi$ and $\pi\pi$ systems. Without going into details

TABLE I (Ref. 11)

$J^P = 2^+$ SU(3) Comparison

$\theta_o = 10^\circ$, $\theta_2 = 30^\circ$

$2^+ \to 1^- 0^-$	Decay Amplitude	$\Gamma_{\mathrm{exp'tl}}$(MeV)	$\Gamma_{SU(3)}$(MeV)
$A_2(1307) \to \rho\pi$	$\frac{\sqrt{6}}{3} A_a^8$	67.0 ± 7.9	71
$K(1420) \to K(890)\pi$	$\frac{1}{2} A_a^8$	29.4 ± 6.1	24
$K(1420) \to K\rho$	$\frac{1}{2} A_a^8$	10.0 ± 3.3	7
$K(1420) \to K\omega$	$\frac{1}{2} A_a^8$	3.1 ± 2.5	5
$f(1500) \to K(890)K$	$1\ A_a^8 \cos\theta_2$	9.0 ± 9.0	9

$\chi^2 = 2.3$

NC = 4

$2^+ \to 0^- 0^-$			
$A_2(1307) \to K\bar{K}$	$\frac{\sqrt{15}}{5} A_s^8$	6.5 ± 1.3	7.3
$A_2(1307) \to \pi\eta$	$\frac{\sqrt{10}}{5} A_s^8 \cos\theta_o - 1\ A_1^o \sin\theta_o$	16.5 ± 3.0	14.0
$A_2(1307) \to \pi\eta'$	$\frac{\sqrt{10}}{5} A_s^8 \sin\theta_o + A_1^o \cos\theta_o$	0.0 ± 2.7	0.0
$K(1420) \to K\pi$	$\frac{3}{\sqrt{10}} A_s^8$	62.5 ± 7.5	64.0
$K(1420) \to K\eta$	$\frac{1}{\sqrt{10}} A_s^8 \cos\theta_o$	0.0 ± 1.3	2.0
$f(1250) \to \pi\pi$	$\sqrt{3}\ \{\sqrt{\frac{1}{8}} A_1 \cos\theta_2 - \sqrt{\frac{1}{5}} A_s^8 \sin\theta_2\}$	150.0 ± 15.0	152.0
$f(1250) \to K\bar{K}$	$1\ \{\frac{1}{\sqrt{2}} A_1 \cos\theta_2 + \sqrt{\frac{1}{5}} A_s^8 \sin\theta_2\}$	- - -	7.0
$f(1250) \to \eta\eta$	$-1\ \{\sqrt{\frac{1}{8}} A_1 \cos\theta_2 + \sqrt{\frac{1}{5}} A_s^8 \sin\theta_2\} \cos^2\theta_o$	- - -	0.0
$f(1500) \to \pi\pi$	$-\sqrt{3}\ \{\sqrt{\frac{1}{8}} A_1 \sin\theta_2 + \sqrt{\frac{1}{5}} A_s^8 \cos\theta_2\}$	0.1 ± 7.0	2.5
$f(1500) \to K\bar{K}$	$1\ \{-\frac{1}{\sqrt{2}} A_1 \sin\theta_2 + \sqrt{\frac{1}{5}} A_s^8 \cos\theta_2\}$	69.0 ± 25.0	45.0
$f(1500) \to \eta\eta$	$1\ \{\sqrt{\frac{1}{8}} A_1 \sin\theta_2 - \sqrt{\frac{1}{5}} A_s^8 \cos\theta_2\} \cos^2\theta_o$	0.1 ± 7.0	12.0

$\chi^2 = 7.4$

NC = 6

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here, it has already been reasonably well established[14] that, at least below 1 GeV, the exotic isospin-3/2 $K\pi$ and isospin-2 $\pi\pi$ systems both exhibit slowly varying fairly small negative S-wave phase shifts. The nature of the isospin-1/2 $K\pi$ and isospin-zero $\pi\pi$ S-wave amplitudes have however been a matter of rather more controversy and difficulty, and are continuing to be a subject of considerable study.

I want first to take up the recent analyses of the $K\pi$ system. Recent work by the ANL-Chicago bubble chamber group based principally on the reaction of Fig. 7a using their own data at 5.5 GeV/c has already been published.[15] I actually want to mention in somewhat more detail work by the CERN-Brussels-UCLA Collaboration[16] using the reactions of Fig. 7b with an enormous sample of events coming from the so-called "World Data Tape" encompassing incident K^+ momenta ranging from 3 to 13 GeV/c. The available total number of $K^+p \to K^+\pi^-\pi^+p$ events, namely 77,267, gives some idea of the magnitude of the statistics involved. The Johns Hopkins Group has made a somewhat similar analysis,[17] based on about 60% of the events presently available on the World Data Tape, but because of the larger statistics and my own greater familiarity with that work I shall confine my discussion to the CERN-Brussels-UCLA work.

The analysis is based on the assumption of only S and P waves below 1 GeV mass and the absence of inelasticity. $K\pi$ angular distributions are parametrized by their average moments $\langle Y_1^0(\theta)\rangle$ and $\langle Y_2^0(\theta)\rangle$ which are themselves simply related to the phase shifts. These moments are extrapolated from the physical region to the pion pole. For this study of $K\pi$ scattering, the $p\pi^+$ system is confined to the $\Delta^{++}(1236)$ mass region. Before going to the results it is worth noting that the large data sample of the World Tape permits tests of the self-consistency of the procedure which perhaps increases potential confidence in the results:

(i) The moments $\langle Y_1^0\rangle$ and $\langle Y_2^0\rangle$ must be independent of the incident momentum of the K^+ meson. The experimental verification of this expectation between 3 and 13 GeV/c is shown in Fig. 8.

(ii) The application of a similar procedure to the study of π^+p scattering from the same reaction (keeping now the $K^+\pi^-$ in the $K^*(890)$ region) should give results in agreement with the accurate ones available

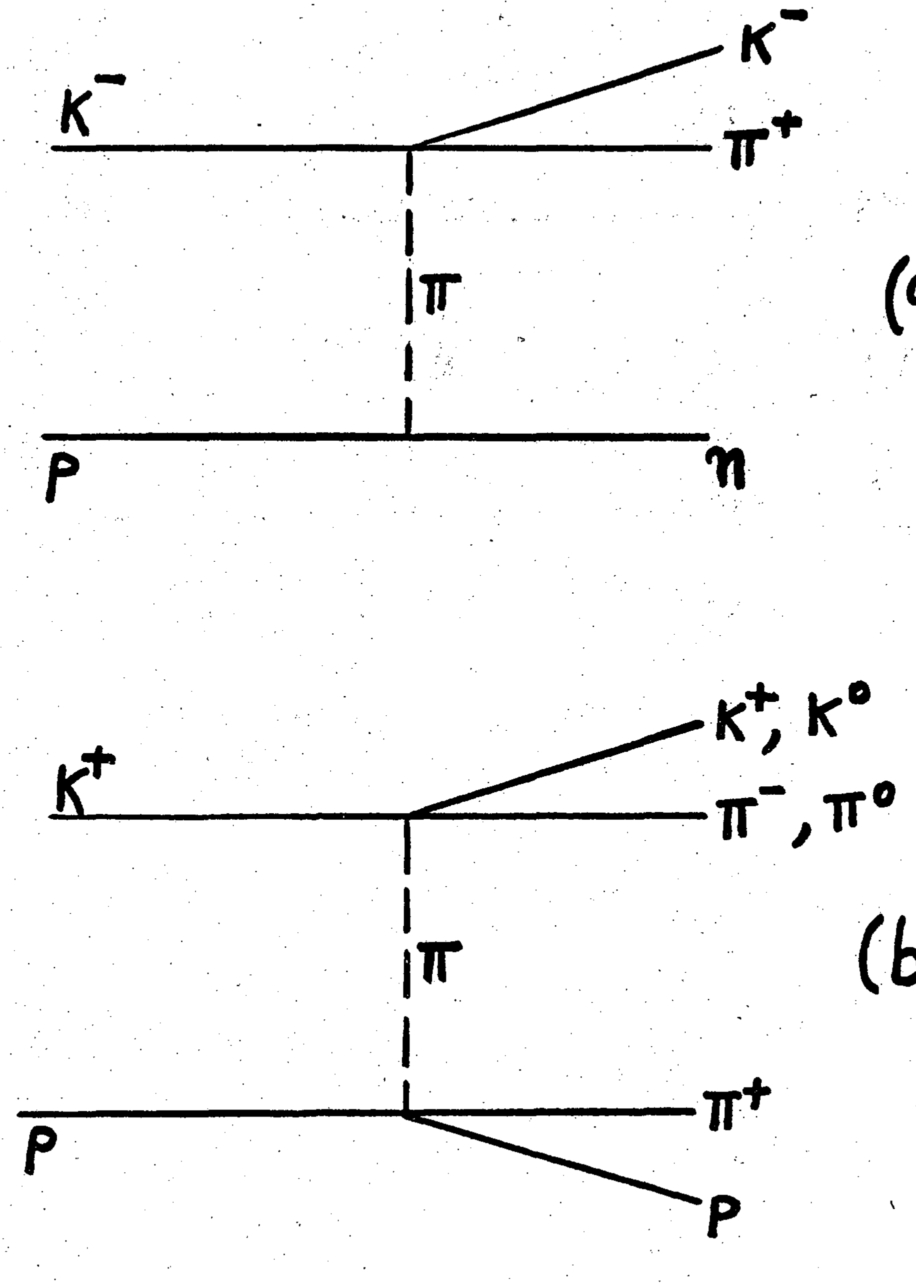

Fig. 7. Kπ scattering via one-pion-exchange.

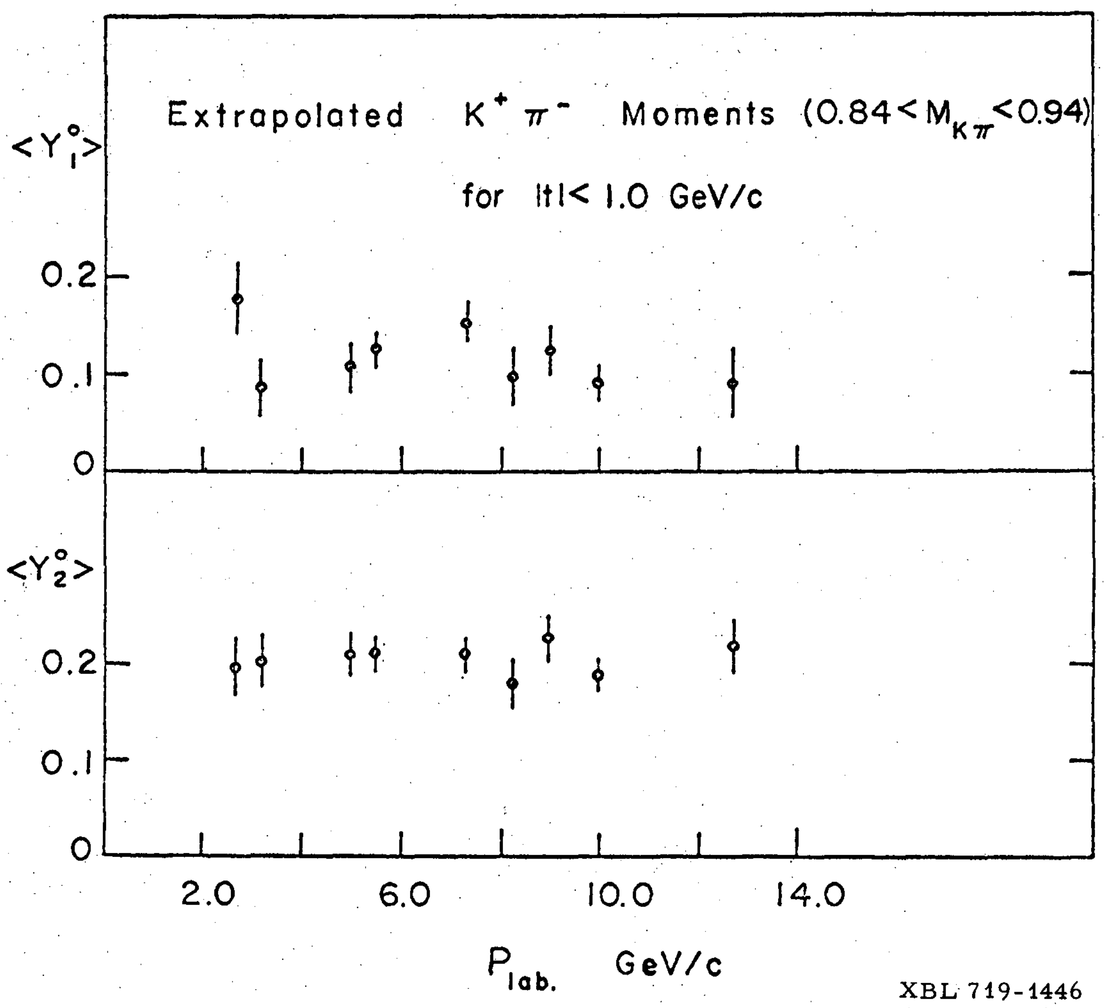

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Fig. 8. Momentum dependence of $K^+\pi^-$ moments.[16]

directly from formation experiments. Such a comparison is shown in Fig. 9 for $p\pi^+$ masses up to 2.2 GeV and moments up to $\langle Y_4^0 \rangle$. The agreement, although not perfect, seems rather good enough to inspire some confidence in $K\pi$ scattering results obtained in the same manner.

(iii) Although the CERN-Brussels-UCLA results[16] have not yet been shown I want to anticipate to the extent of saying that they do seem to agree with those from the ANL-Chicago Group[15] which uses a completely different reaction with incident K^- instead of K^+.

Before going to these results I want to allude here to a potential difficulty about which I believe there exists more confusion than is really warranted. It is known that the $K^+\pi^-\Delta^{++}$ final state is dominated at high energy by a very strong $\pi^-\Delta^{++}$ diffractive dissociation of the incident nucleon, just as the $K^*(890)\ \pi^+ p$ final state is dominated by the diffractive dissociation of the incident K^+, the so-called Q bump. Similarly at high energy the $K^- n \to K^- \pi^- p$ final state contains a strong low $p\pi^-$ enhancement which presumably is a diffractively dissociated incident neutron. These enhancements all reflect strongly into the forward part of $K\pi$ scattering (nucleon dissociation) or πp scattering (K dissociation). In the CERN-Brussels-UCLA work, as in much other work, it is simply assumed that whatever nefarious effects these reflections cause disappear upon extrapolation to the pole. My essential point is that although the reflections of diffractively produced structures do <u>not</u> disappear upon extrapolation, they are in fact an essential part of the $K\pi$ or $\pi\pi$ scattering one is studying. One should not in any case attempt to subtract them out as though they were incoherent background. I feel somewhat impelled to discuss this point in some detail because it will arise even more strongly in the later discussion of higher mass boson states.

Thus consider, in Fig. 10a, a diagram which might represent the diffractive dissociation of p into $\Delta^{++}(1236)\pi^-$ via Pomeron exchange in the reaction of interest. In the region of very low momentum transfer between incident p and final Δ one might expect the diagram of Fig. 10a to be dominated by a contribution of the form of Fig. 10b; here I have drawn heavily on the type of analysis made by Chew and Pignotti.[18] If we now go to the limit of small $K\pi$ subenergy, namely the domain of interest here, the $K\pi$ scattering via Pomeron exchange indicated in

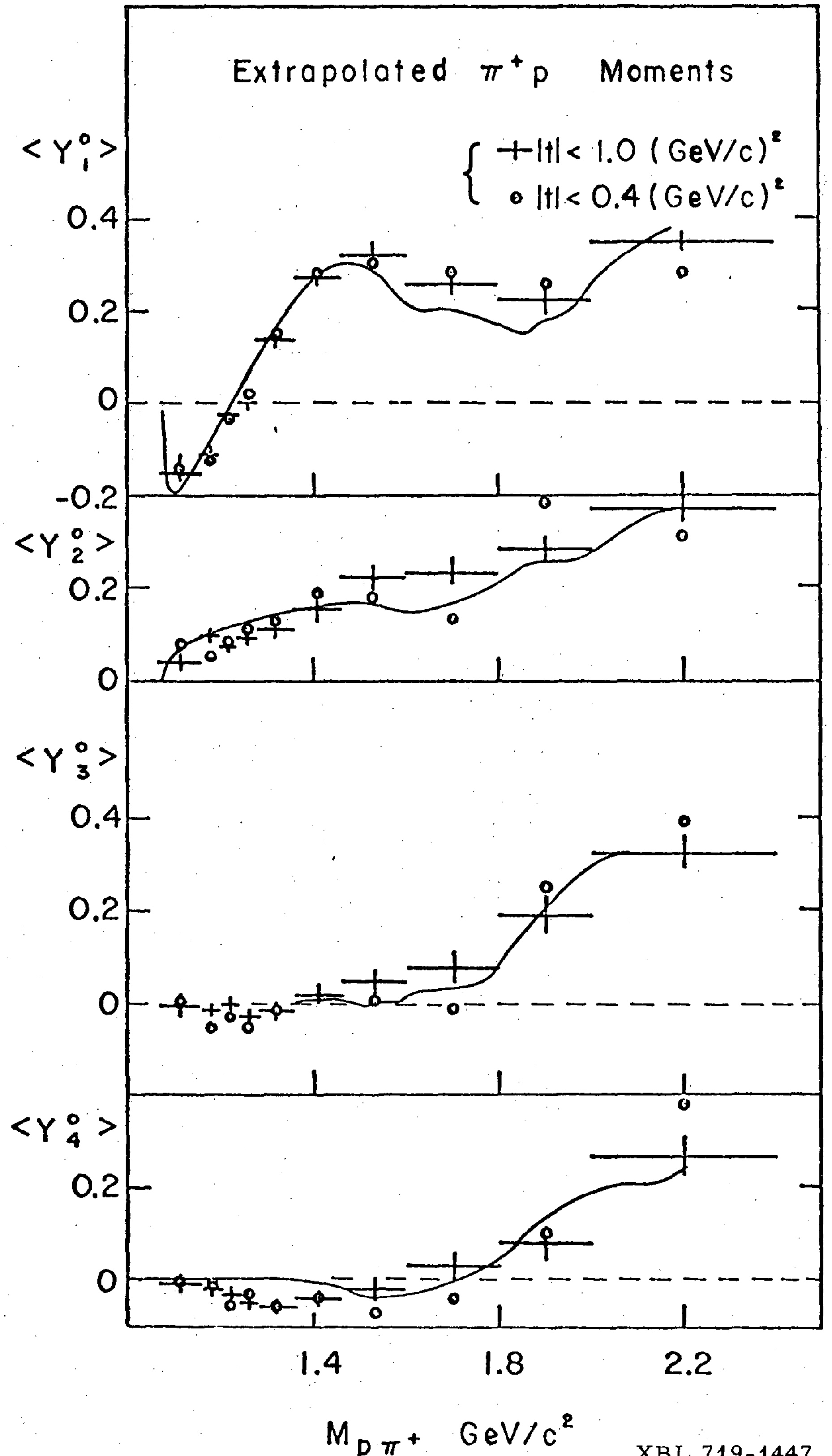

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Fig. 9. Extrapolated pπ^+ moments vs phase shift solution.

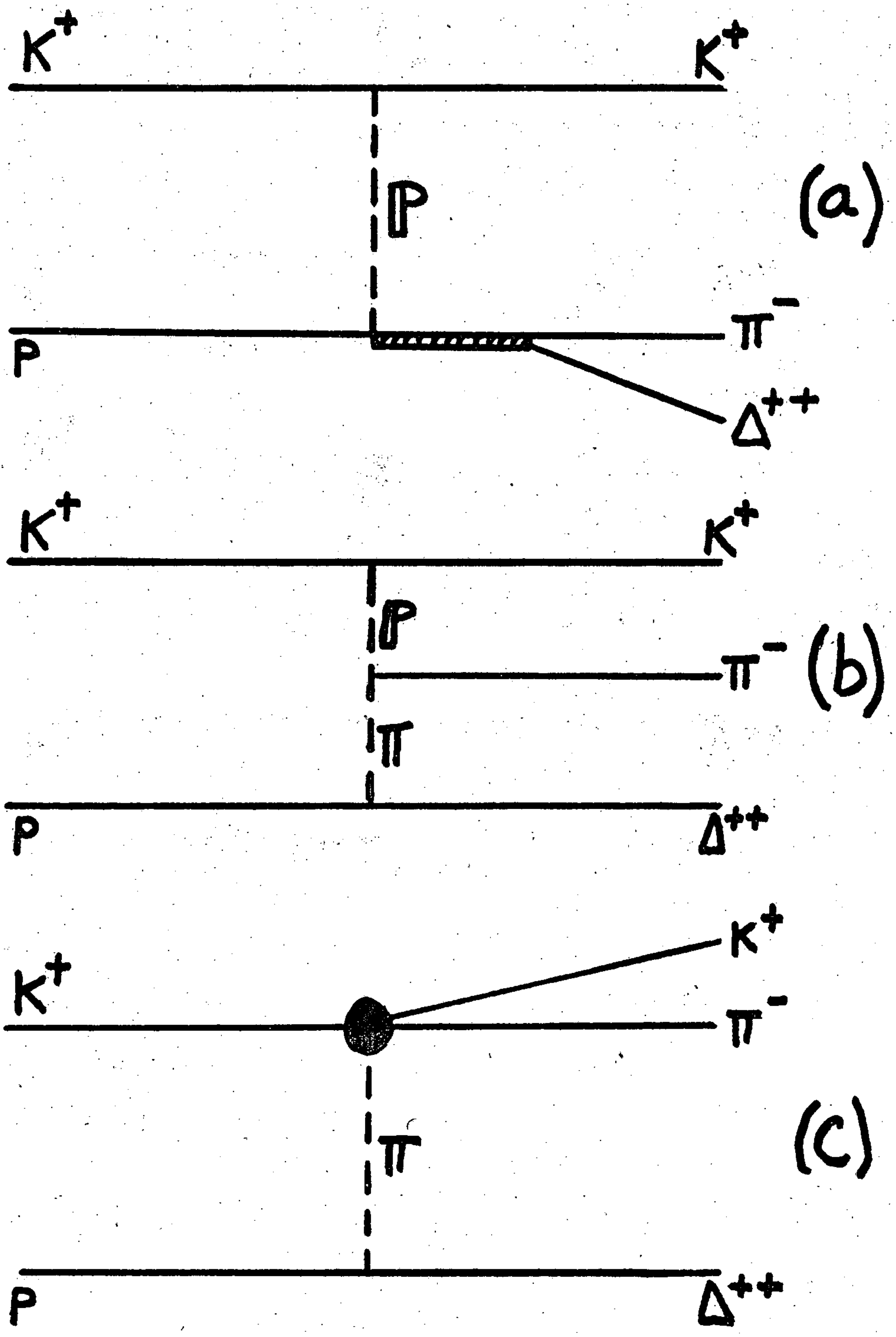

Fig. 10. Relation between nucleon dissociation and Kπ scattering.

the upper half of the diagram of Fig. 10b simply becomes, via the duality arguments of Harari and Freund[19] the nonresonant part (for example, isospin-3/2) of the Kπ amplitude (see Fig. 10c). This amplitude is a coherent part of the overall Kπ scattering and must be retained in any attempted phase-shift analysis of meson-meson scattering. In other words the reflection of the diffractive nucleon dissociation forms an integral part of Kπ scattering just as the reflection of the kaon dissociation is an essential part of the pion-nucleon scattering.

Having made these remarks, both experimental and quasi-theoretical, which in my mind help justify the validity of results on meson-meson scattering via one-pion-exchange extrapolations, I now come to the results. Those of the CERN-Brussels-UCLA Collaboration are shown in Fig. 11 which exhibits the isospin-1/2 S-wave Kπ phase shift between 0.78 and 1.04 GeV. An S-wave isospin-3/2 negative phase shift with a cross section of 1.8 mb, in agreement with other data has been assumed as has a Breit-Wigner shape with mass 891 MeV, width 50 MeV for the K*(890). There are two ambiguous solutions, one exhibiting a sharp resonance just on top of the K*(890) and the other a slow, gradual rise to about 60° at 1.04 GeV. These ambiguous solutions are also features of both the Johns Hopkins analysis[17] and the ANL-Chicago analysis.[15] There is unfortunately no easy way from existing Kπ data to make a choice although, since as will be seen further, ππ scattering data definitely do <u>not</u> favor the sharp resonance solution, SU(3) arguments strongly argue in favor of the slowly rising phase shift. It is worth mentioning in passing that both Trippe et al.[20] and Firestone et al.[21] have suggested actual resonant S-wave behavior at considerably higher energy (~ 1150-1350 MeV) than that presently under consideration. Unfortunately higher waves and inelasticities then set in and greatly limit the degree of detail achievable and exhibited for lower energies in Fig. 11.

While no World Data Summary Tape has, to my knowledge, been constructed recently for studies of ππ scattering the accumulation of very extensive statistics at fixed energies by several groups has also led to interesting results. As an example, Fig. 12 shows the isospin-zero, S-wave ππ phase shifts from a very recent analysis by a SLAC

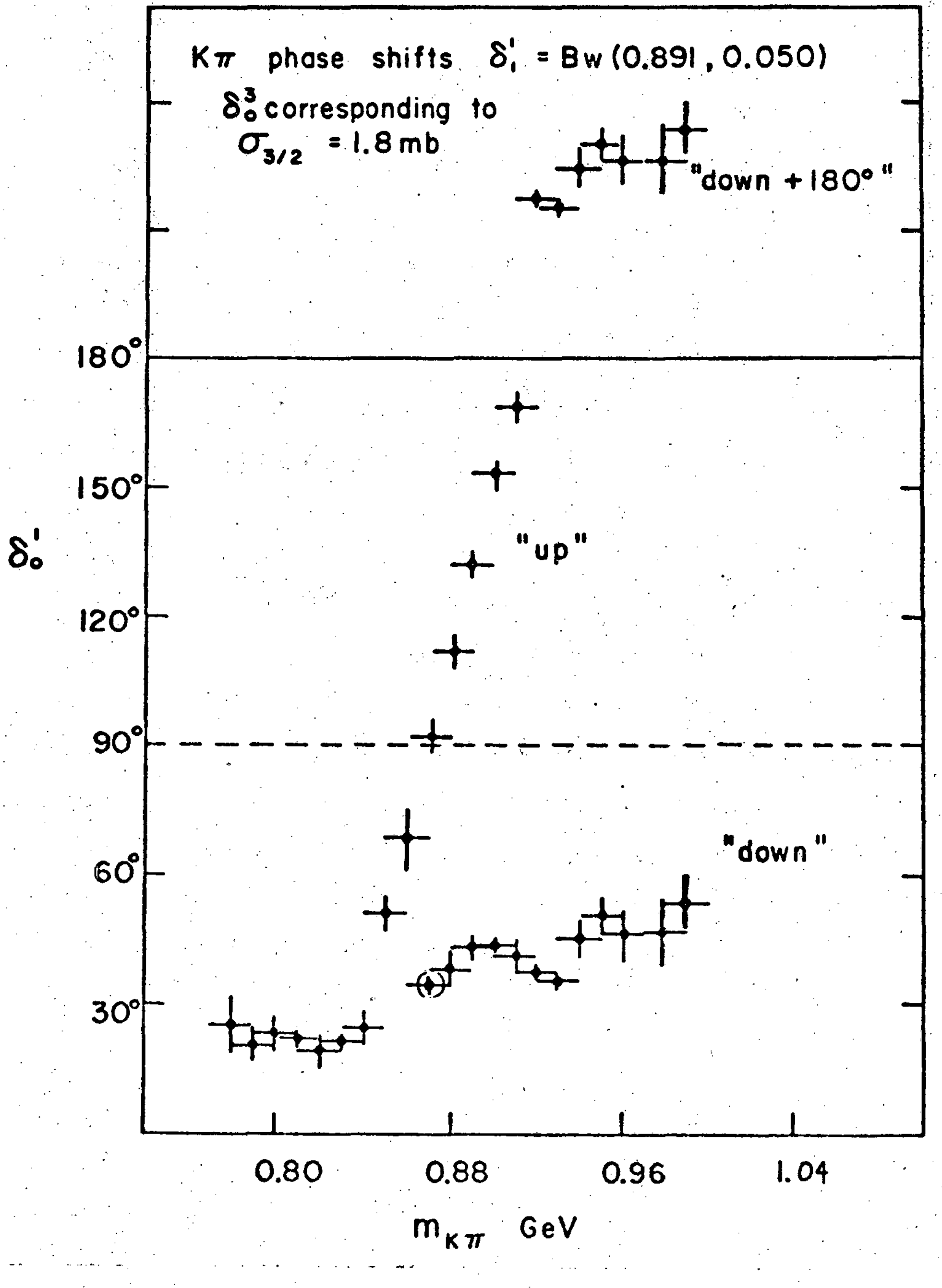

Fig. 11. Isospin-1/2 S-wave Kπ phase shift.[16]

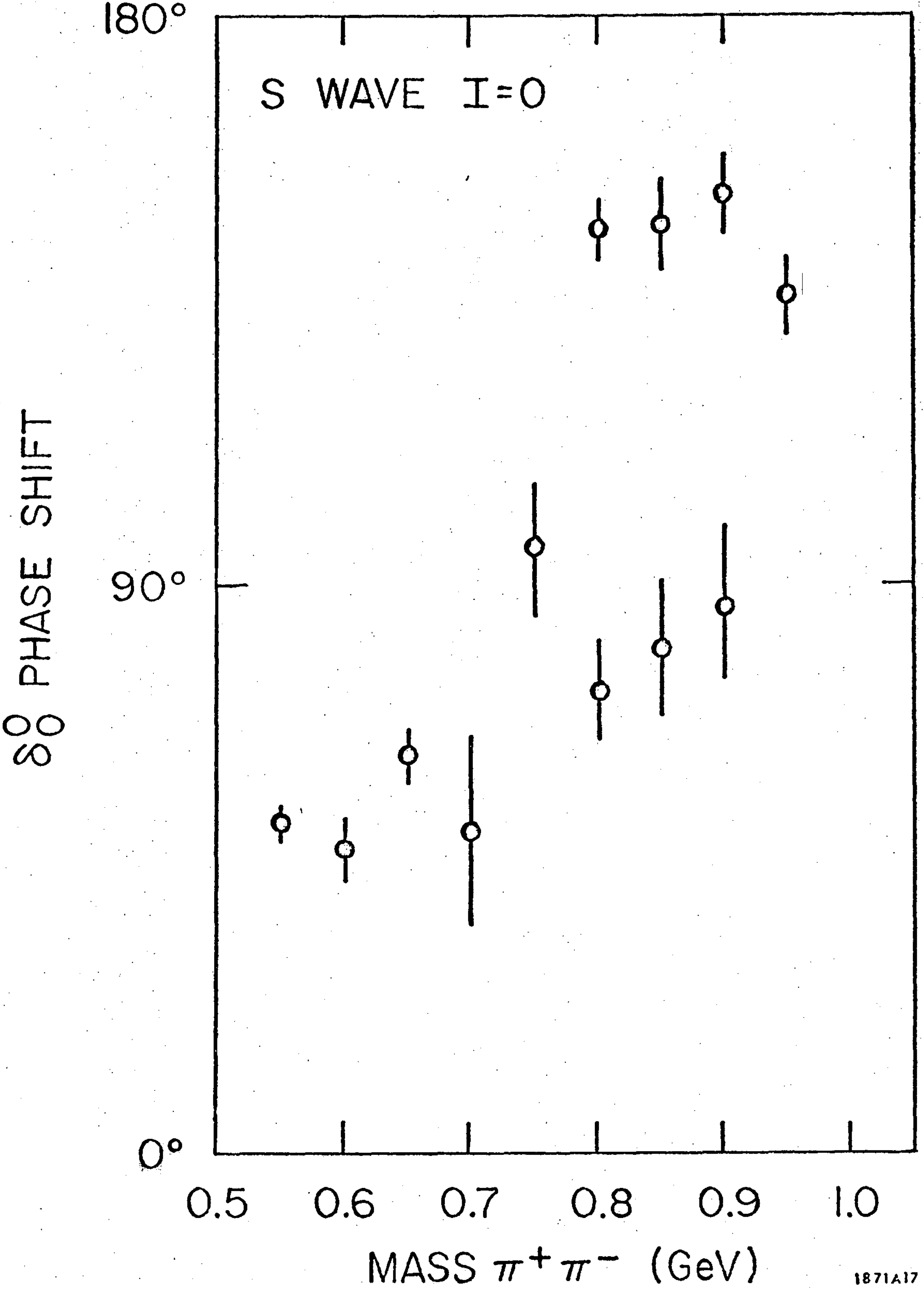

Fig. 12. S-wave $\pi\pi$ phase shift.[22]

Group, Baillon et al.,[22] using the results of a wire chamber spectrometer study of the reaction $\pi^- p \to n\pi^+\pi^-$ at 15 GeV/c. These agree reasonably with those recently published by Baton et al.[23]; and, as in the $K\pi$ case, exhibit a two-fold ambiguity at the higher masses, one solution representing a sharp resonance essentially coincident with the ρ and the other a slowly rising phase shift making its way toward about 90° near 900 MeV; unlike the $K\pi$ system however it appears clearly possible to choose the slowly rising amplitude as almost surely the correct one.

This arises first of all from the fact that the $\pi^0\pi^0$ system is capable of showing up an isoscalar S-wave resonance free of contamination by the ρ. While experiments to study the $\pi^0\pi^0$ system are difficult, I am not aware of any which show up a sharp resonance of the sort predicted by the "up" solution of Fig. 12.[24] While details differ from experiment to experiment, observed $\pi^0\pi^0$ mass spectra do seem to follow the flat form indicated by the "down" solution.

Recently further very detailed information relevant to $\pi\pi$ scattering at energies near the $K\bar{K}$ threshold has come from the LBL Group A 7-GeV/c π^+p bubble chamber experiment, other results of which have already been shown in Figs. 3 and 4. Figures 13a,b,c[25] show the mean values of the moments $\langle Y_1^0\rangle$ and $\langle Y_2^0\rangle$ and the mass spectrum for the $\pi^+\pi^-$ system produced by the reaction,

$$\pi^+ p \to \Delta^{++}(1236)\pi^+\pi^- ,$$

in the physical region with $-t' < 0.1\ (\text{GeV}/c)^2$. The mass intervals are 10 MeV bins, and the basic results are summarized in Table II. All these observations can be understood by imagining an Argand Diagram in which the isoscalar $\pi\pi$ S-wave amplitude is somewhere near the top of the unitary circle at about 950 MeV, rapidly going around in clockwise fashion and reaching $K\bar{K}$ threshold near 180°. It then rapidly becomes inelastic in the production of $K\bar{K}$ states. Further details of this analysis are given in the paper of Alston-Garnjost et al.,[25] but the following points are worth emphasizing:

(a) Independent evidence of large S-wave cross sections for $\pi\pi \to K\bar{K}$ just above threshold has been independently given by the CERN-Munich-Zurich-Hawaii[26] Collaboration.

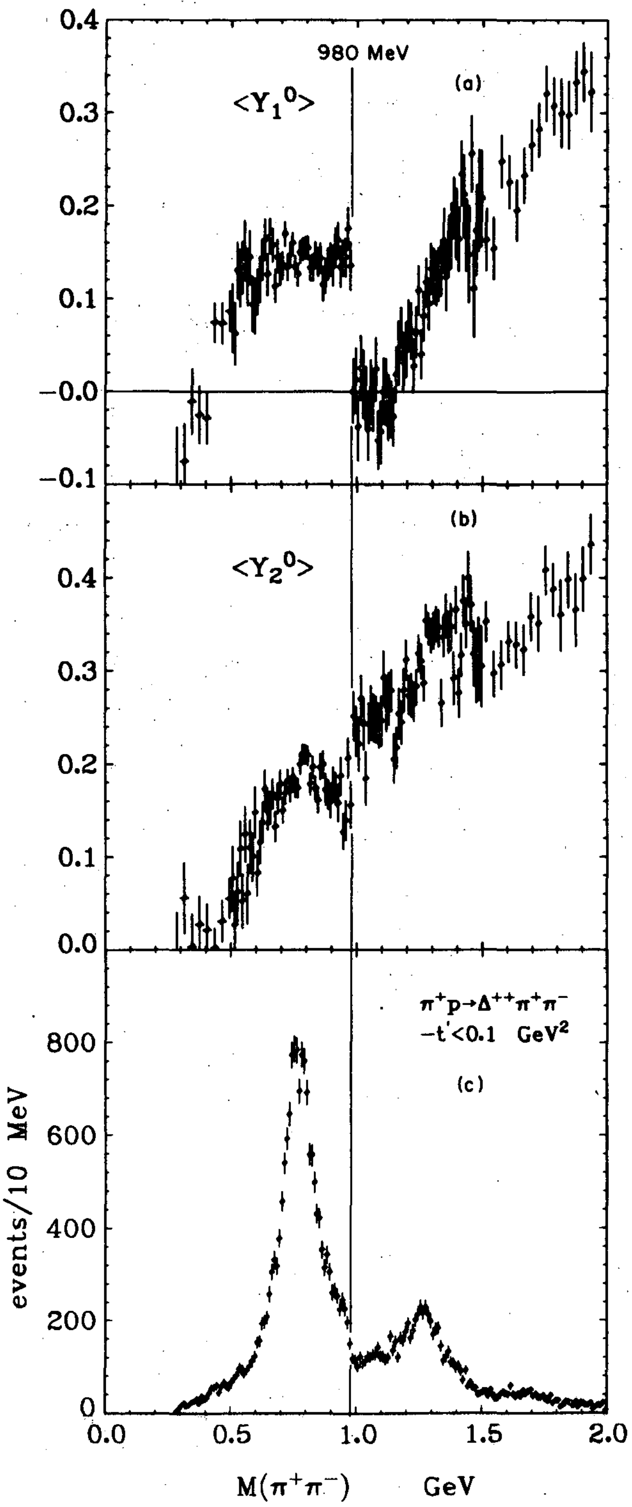

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Fig. 13. $\pi^+\pi^-$ anomaly at $K\bar{K}$ threshold.[25]

Table II. ππ Anomaly Near $K\bar{K}$ Threshold.[25]

Property	Relation to Amplitudes	Behavior
Population	$\|S\|^2 + 3\|P\|^2$	Flat 910-950 MeV Sharp Drop 950-980 MeV
$\langle Y_1^0 \rangle$	$\frac{S \cdot P}{\|S\|^2 + 3\|P\|^2}$	Near-Discontinuity down to zero at 980 MeV
$\langle Y_2^0 \rangle$	$\frac{\|P\|^2}{\|S\|^2 + 3\|P\|^2}$	Sharp Rise at 980 MeV after some previous slight drop

(b) The behavior exhibited by the moments $\langle Y_1^0 \rangle$ and $\langle Y_2^0 \rangle$ in Fig. 13 has also been observed in the SLAC 15-GeV/c $\pi^- p \rightarrow n\pi^+\pi^-$ experiment.[22]

(c) The population behavior near 950 MeV (Fig. 13c) requires a large S-wave amplitude at that energy, in agreement with the "down" but not the "up" solution of Fig. 12.

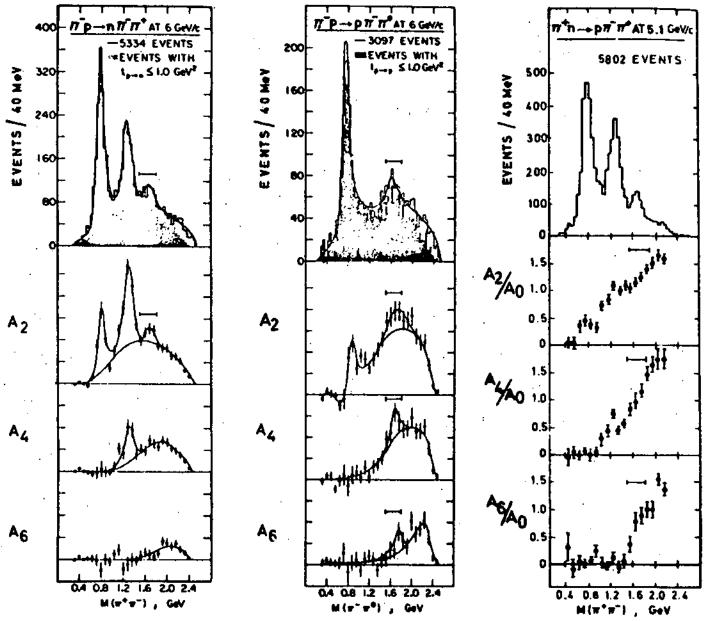
These observations of ππ behavior, coupled with SU(3), are strongly suggestive that the "down" solution for Kπ scattering is probably the correct one.

In conclusion it is fair to say that good experimental data and increased theoretical understanding have the potential of bringing us to a really detailed understanding of the behavior of all Kπ and ππ partial wave amplitudes in at least this energy region below and around 1 GeV.

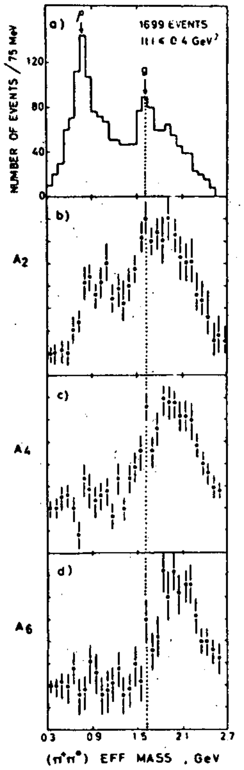
IV. HIGHER ENERGY AND ANGULAR MOMENTUM ππ AND Kπ SCATTERING

Evidence for a natural spin-parity isovector meson of mass around 1650 MeV, which would naturally be interpreted as the Regge recurrence of the ρ meson, has been accumulating for some time. Various sets of data collected by the Aachen-Berlin-CERN Collaboration,[27] including their own results, are shown in Fig. 14. The various data show both mass spectra plus coefficients of Legendre expansions of ππ scattering angular distribution in the physical region. The basic results of all these data are:

(1) There are clearly mass enhancements in $(\pi\pi)^\pm$, $(\pi\pi)^0$ systems



Variation of the Legendre polynomial coefficients for the $\pi^+\pi^-$ and $\pi^-\pi^0$ systems as a function of the dipion mass. The corresponding mass spectra are shown on top of each figure [3,9].



Variation of the Legendre polynomial coefficients for the $\pi^+\pi^0$ system in the reaction $\pi^+p \to p\pi^+\pi^0$ at 8 GeV/c, as a function of the dipion mass. The condition $|t| \leq 0.4$ GeV^2 has been imposed.

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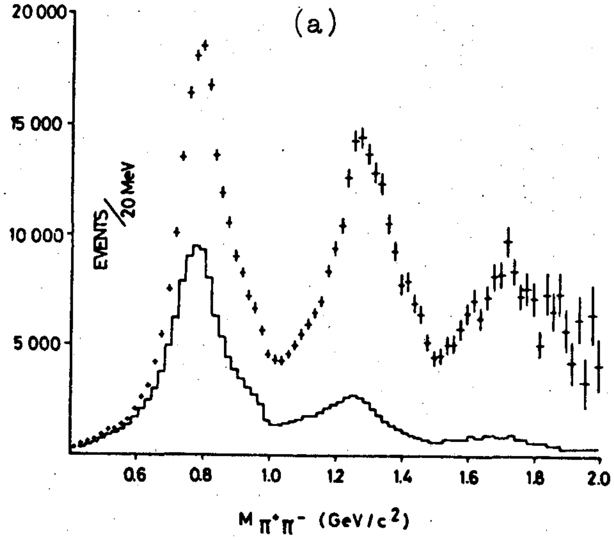
Fig. 14. Properties of $\pi\pi$ systems.[27]

around 1650 MeV. Although not shown in Fig. 14, there is no observed structure in $(\pi\pi)^{++}$ or $(\pi\pi)^{--}$ systems. A most natural interpretation is then the existence of an isovector state of mass near 1650 MeV, usually referred to as the g meson, produced readily in reactions of the form $\pi N \rightarrow \pi\pi N$. Bose statistics then require a spin belonging to the sequence 1, 3, 5, ... etc.

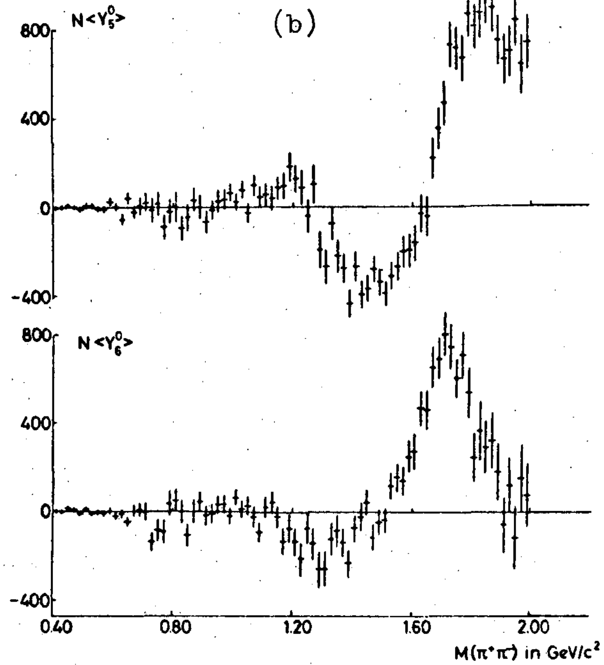
(2) The Legendre expansions of $\pi\pi$ angular distributions show contributions up to but not higher than sixth order at masses up to 2 GeV. Sixth-order contributions definitely become significant just below 1.6 GeV and are thus highly suggestive of the quantum numbers $J^P = 3^-$. It must be stressed however that the behavior of the sixth-order term (which would, assuming pion exchange and no higher order amplitude, be just proportional to $|F|^2$) does not show in any of the experiments of Fig. 14 convincing structure at 1650 MeV. This term simply rises and just tends to remain high up to the point where kinematic limits come into play to turn the reaction off. This suggests that higher than F-wave amplitudes are not completely negligible.

This brings me to the discussion of a recent result from the CERN-Munich Group[28] from a study of the reaction $\pi^- p \rightarrow \pi^+\pi^- n$ at 17 GeV/c by means of counters and spark chambers. The $\pi^+\pi^-$ mass spectrum below 2.0 GeV is shown in Fig. 15a before and after correction for detection efficiency. The Legendre coefficients $N\langle Y_5^0\rangle$ and $N\langle Y_6^0\rangle$ calculated for $-t < 0.2\ (\text{GeV}/c)^2$ (which fundamentally correspond to coefficients A_5, A_6 in Fig. 14) are shown in Fig. 15b. Higher-order moments given in the CERN-Munich paper appear to be negligible in the $\pi\pi$ mass range below 2.0 GeV. It is pointed out by the authors that the structure shown in Fig. 15a and 15b gives conclusive evidence for the spin 3 assignment of the g meson. It is however only fair to point out that there are some mysteries (at least in my mind) about the CERN-Munich results:

(i) As specifically noted by the authors, $\langle Y_6^0\rangle$ is significantly negative (if one believes the quoted errors) around 1.2 to 1.4 GeV. In the absence of waves above the F-wave this is hard to understand in the context of one-pion-exchange. The authors, while not certain of the explanation of this effect, assert that its resolution should not affect their conclusion.



Dipion mass distribution of observed events with $|t| < 0.2$ (GeV/c)^2 (lower curve), and corrected for acceptance losses (upper curve) using a fit with $l_{max} = 6$, $m_{max} = 1$.



The moments $N\langle Y_l^0\rangle$ for $|t| < 0.2$ (GeV/c)^2 ($l_{max} = 6$, $m_{max} = 1$).

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Fig. 15. $\pi^+\pi^-$ properties.[28]

(ii) The behavior of $\langle Y_6^0\rangle$ near 1.9-2.0 GeV shown in Fig. 15b is totally different from that in any of the bubble chamber experiments. Inspection of Fig. 14 shows that $\langle Y_6^0\rangle$ or $N\langle Y_6^0\rangle$ tend to be maximal near 2.0 GeV whereas the CERN-Munich Group finds this quantity to be zero. Since it is in large part the observed structure in $N\langle Y_6^0\rangle$ which leads the CERN-Munich Group to its definitive conclusion, the clarification of this point appears to be of some importance.

(iii) Finally, and this may relate to point (ii) above, it is noted as an asset by the CERN-Munich Group that their apparatus is insensitive to $n\pi^{\pm}$ masses below 1.5 GeV. As I pointed out in Sec. III and Fig. 10 the proton diffractive dissociation into low mass $n\pi^{+}$ is an essential and coherent part, not a superfluous reflection, of the $\pi\pi$ scattering. I am simply unsure as to how the correction for this loss is made.

In conclusion, insofar as the g-meson is concerned, it appears quite convincing from the data of Fig. 14 and Fig. 15, as well as other data not shown here, that the spin-parity 3^{-} assignment is the correct one. It would however be desirable to go a large step further, as one does in pion-nucleon phase-shift analysis, by making an actual partial-wave break-up of the amplitudes which go into the Legendre coefficients shown in Figs. 14 and 15. Unfortunately one suffers in that the data of Fig. 14 cover a t-range which is a bit too high for simple pion-exchange dominance ($\lesssim 1.0\ (\mathrm{GeV}/c)^2$ which is another way of saying that the interesting statistics are low) whereas those of Fig. 15 require resolution of the questions (i), (ii), (iii) mentioned above before a completely believable analysis can be made. These problems preclude at present answers to such questions as whether the g-meson might be hiding underneath it resonances of lower angular momentum. It is also important to note that the g-meson has substantial decay modes other than 2π. New information on these has been presented on these elsewhere at this Conference,[29] and I shall make no further comment on them here.

The previous discussion of the g-meson as the Regge recurrence of the ρ immediately raises the question as to the strange counterpart which would be the Regge recurrence of the $K^*(890)$. By analogy with the fact that the g shows up in reactions of the form $\pi N \rightarrow \pi\pi N$, it is not surprising that evidence for a strange 3^- meson has shown up in studies of Kπ systems from the reaction

$$K^+n \rightarrow K^+\pi^-p \quad .$$

Indeed independent evidence for such a particle has come from the Purdue-Davis-Indiana Group[30] (9 GeV/c) and the LBL Group (Firestone et al.).[31] Mass spectra from both these groups for the above reaction are shown in Fig. 16. It is clear that there is substantial evidence of structure in the region around 1700-2000 MeV. Figure 17 from the work of the LBL Group shows Legendre coefficients $N\langle Y_\ell^0\rangle$ up to sixth order (higher order is negligible up to 2.2 GeV). The resemblance between the behavior of the coefficients in Fig. 17 and the available corresponding ones in Fig. 14 is striking. Again $N\langle Y_6^0\rangle$ rises substantially in the region under consideration although, analogously to Fig. 14 but not Fig. 15 it does not exhibit structure parallel to the shape of the Kπ mass spectrum. There is also in Fig. 17 in the $N\langle Y_3^0\rangle$ and $N\langle Y_5^0\rangle$ terms evidence of strong and rapidly varying interference effects in the 1800 MeV Kπ mass region. I think that it is fair to conclude that these data are highly suggestive of a strange analogue to the g-meson in the mass region 1750-1850 MeV.[32] It is interesting to note that such a state would nearly complete a 3^- nonet. An ω(1680), presumably the recurrence of the ω(782), has been reasonably well established,[33] and it only remains to find the recurrence of the φ(1020). It is also worth noting that a detailed partial wave analysis of distributions such as that in Fig. 17 is eventually desirable to see if lower angular momentum states are hidden under the dominant resonances. In my view, the increasing success of the lower energy ππ and Kπ phase-shift analysis (see Sec. III) makes this a not-too-unrealistic hope for the future.

V. DIFFRACTIVE PROCESSES

I want to conclude my talk with some fairly brief remarks about states in the unnatural spin parity series produced by diffractive processes. The production of some low-mass baryon resonances in this manner has been studied in inclusive processes with identical incoming and outgoing particles and an appropriate spectrometer to determine momentum transfer and missing mass.[34] Here, however, I want to

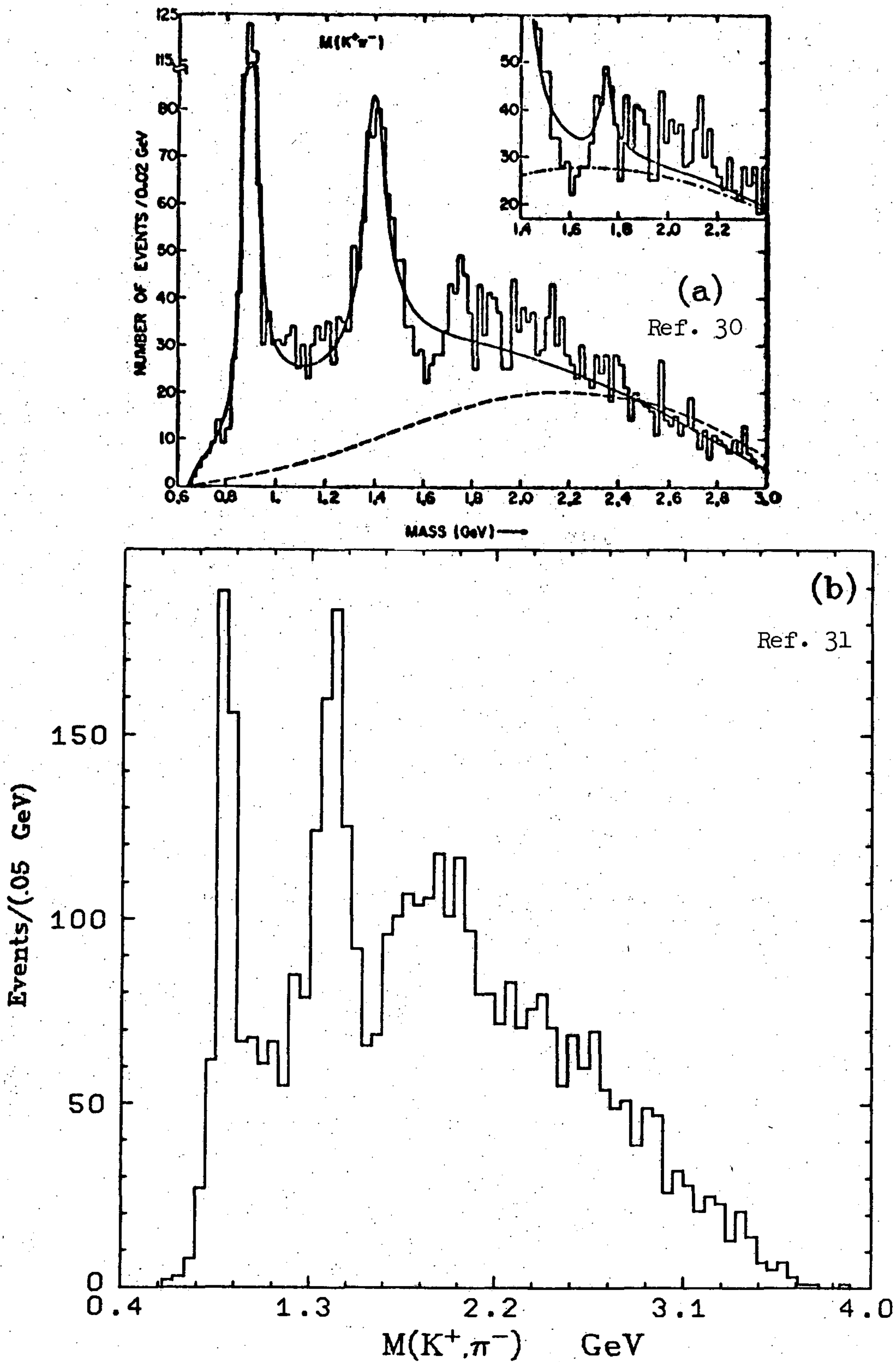

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Fig. 16. $K^+\pi^-$ spectra from $K^+n \rightarrow K^+\pi^-p$.

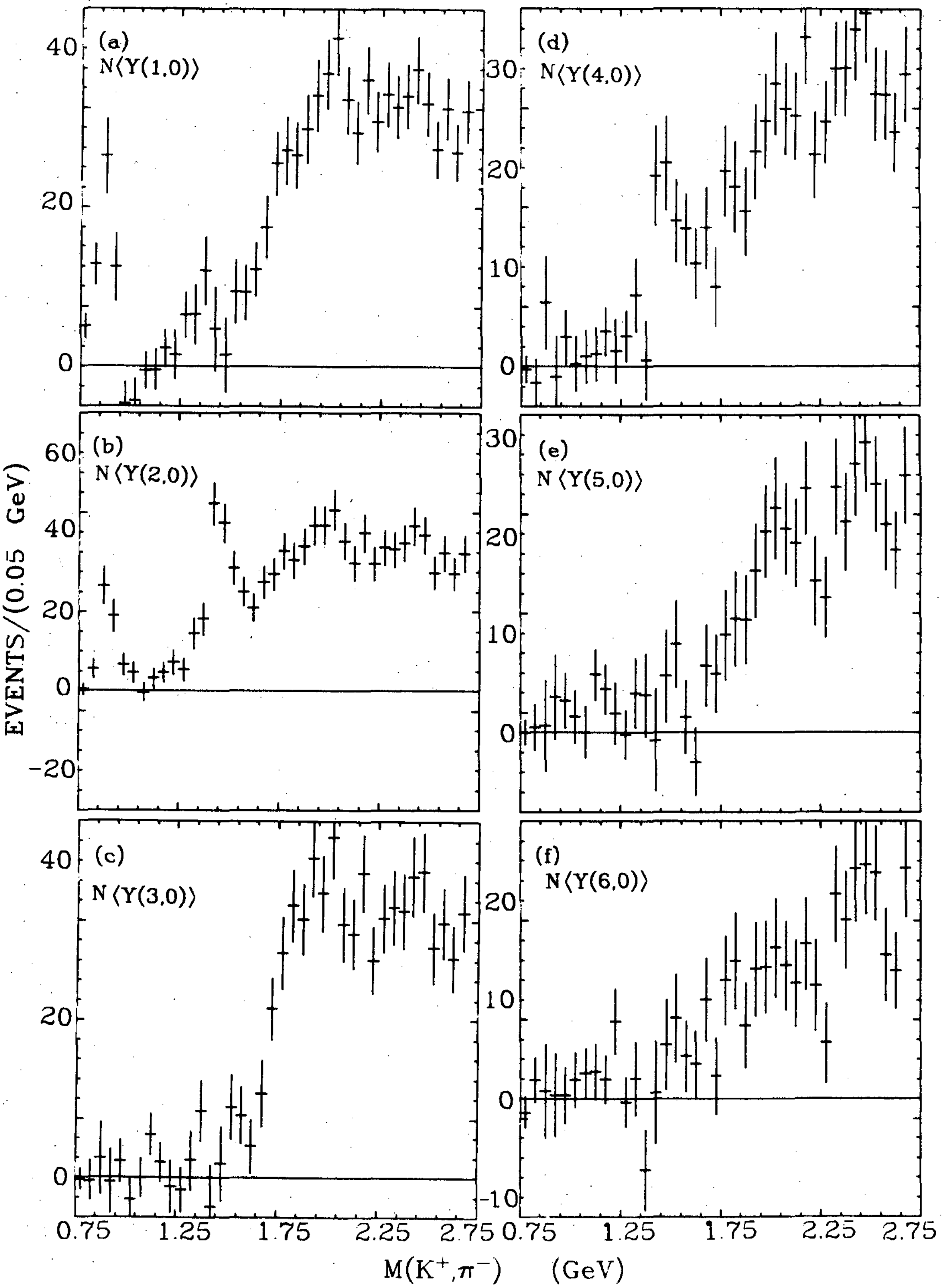

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Fig. 17. $K^+\pi^-$ moments.[31]

emphasize the states produced via "exclusive" three-body processes such as:

$$\pi^{\pm}p \rightarrow A_1^{\pm}p \rightarrow (\rho\pi)^{\pm}p \qquad (3a)$$

$$\pi^{\pm}p \rightarrow A_3^{\pm}p \rightarrow (f\pi)^{\pm}p \qquad (3b)$$

$$K^{\pm}p \rightarrow Q^{\pm}p \rightarrow (K^*(890)\pi)^{\pm}p \qquad (4a)$$

$$K^{\pm}p \rightarrow L^{\pm}p \rightarrow (K^*(1420)\pi)^{\pm}p \quad . \qquad (4b)$$

In referring to the final states as "three-body" I have considered ρ, f, K*(890), K*(1420) as single particles.

Since time is short, I shall simply indicate here very briefly some general features of these processes which have had recent attention:

(1) Mass spectra exhibit large broad enhancements not very much above the thresholds for the combinations indicated in parentheses in the equations (3,4) shown above. These enhancements, which, in the case of the Q and A_1, have been studied quite extensively generally give rough qualitative fits to multi-Regge models. Examples of such fits for the Q have been quoted in the review paper by A. Firestone.[35] Appropriate combinations of Breit-Wigner amplitudes can give much more quantitative fits to the experimental data. Firestone[35] was able to obtain good fits to a large amount of Q^+ data with a combination of two (a single one was clearly inadequate) Breit-Wigner terms. Because of uncertainties about handling of background and further uncertainties about the dynamics of the production process, his actual resonance and width values should be treated with caution.

(2) Spin-parity analyses have given values of 1^+ for the A_1 and Q and 2^- for the A_3 and L. A particularly illuminating way of representing the 3π data in the A_1, A_2, A_3 regions, obtained by the Illinois Group,[36] is shown in Figs. 18a and 18b which use in part Illinois Group data and in part data from other groups, particularly at the higher energies. The 1^+ contributions for the A_1 and 2^- for the A_3 come almost exclusively from S-wave ρπ in the first case and S-wave fπ in the second.

(3) Enough data at various energies have recently been accumulated to examine the energy dependences of the Q and A_1 cross sections with

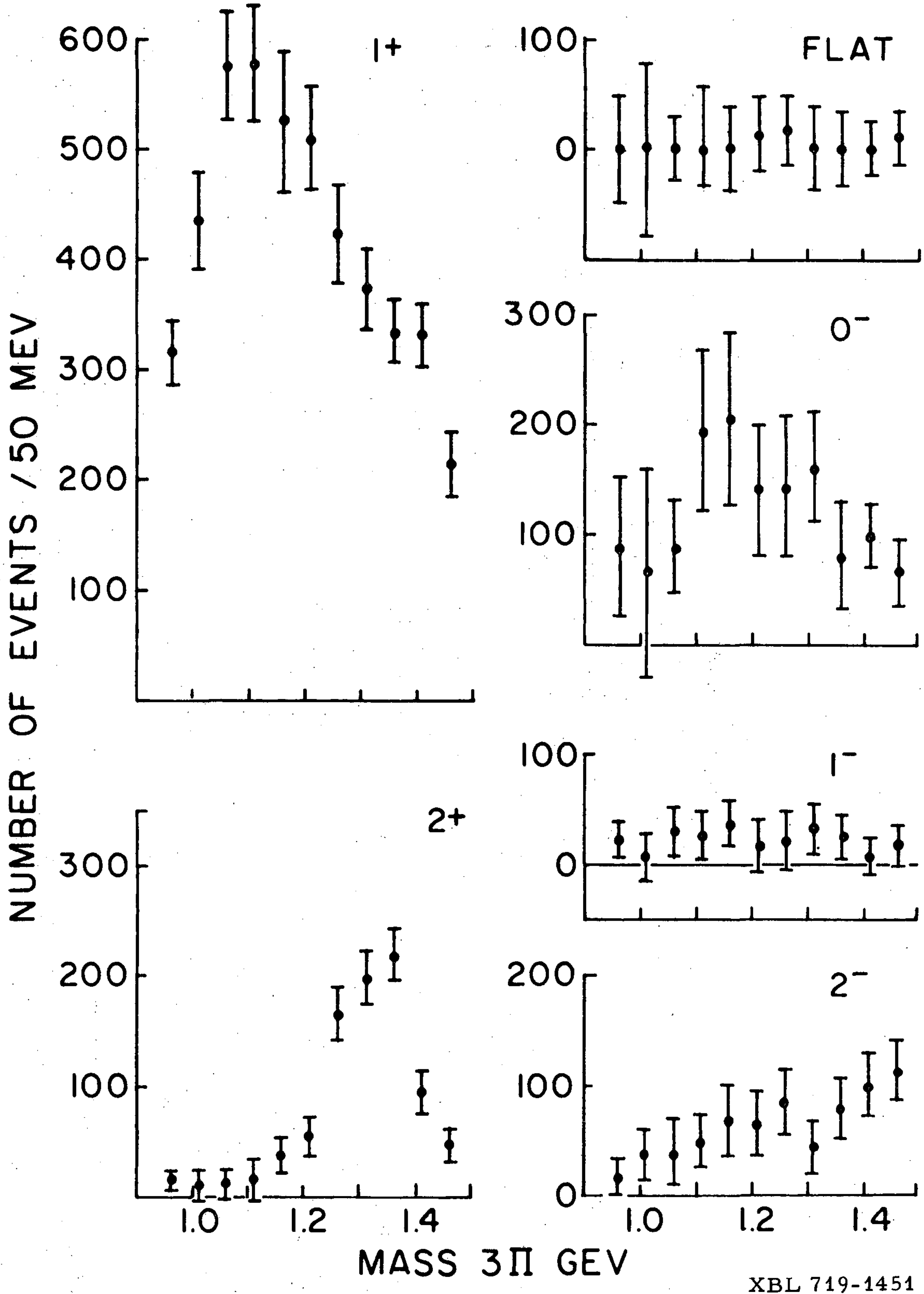

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Fig. 18a. J^P composition of (3π) from $\pi^- p \to p(3\pi)^-$.[36]

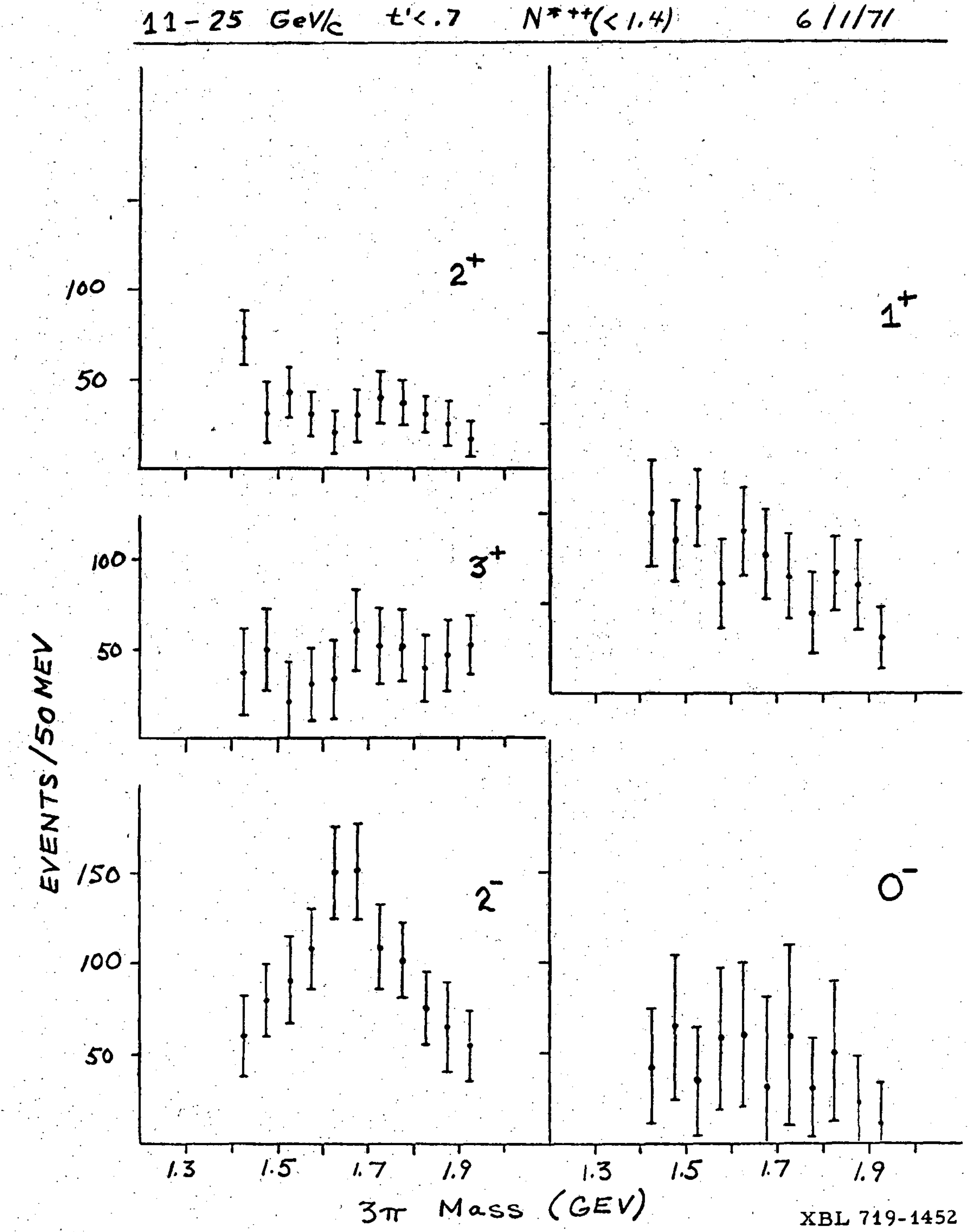

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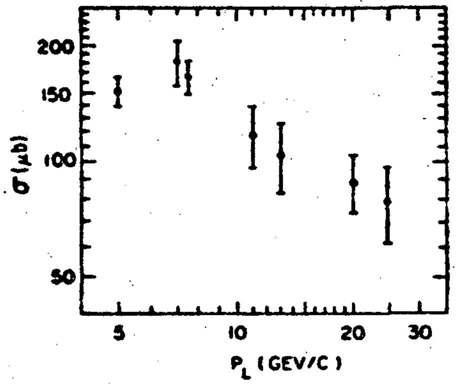
Fig. 18b. J^P composition of (3π) from $\pi^- p \rightarrow p(3\pi)^-$.[36]

some reliability. Results for the A_1 (here defined as the 1^+ component of the 3π amplitude) and the Q (here the results are plotted, mass interval by mass interval, with no background removed)[37] are shown in Figs. 19 and 20. In both cases the cross sections have a slow though nonzero decrease with incident energy. These results are suggestive of dominant Pomeron exchange accompanied by some f, ω exchange. Unsuccessful searches for Q production via charge-exchange processes suggest ρ, A_2 exchange contributions are very small.[38]



The cross section for the reaction $\pi^-p \to A_1^-p$ as a function of the incident π^- momentum with the A_1^- as defined in the text. The cross sections have not been corrected for unseen decay modes of the A_1^-.

Fig. 19. Ref. 36.

(4) Studies of Q production in deuterium could a priori lead to a different mass spectrum if two distinct resonances produced via different exchanges represent the spectrum seen in hydrogen collisions.[39] Evidence from several experiments[40] (see for example Fig. 21 for data at 12 GeV/c from Firestone et al.[40]) show no such effect; mass spectra from deuterium are practically identical to those in hydrogen.

What can we say at this point as to the resonant or nonresonant nature of enhancements such as the Q or A_1? The subject is still controversial, and I can at best venture some opinions: my belief is that indeed such structures are resonant, the arguments being the following:

(i) The shapes of the structures, particularly their drops at the higher masses have a sharpness which seems, at least to me, most easily understood in terms of resonant amplitudes. As pointed out by Chew and

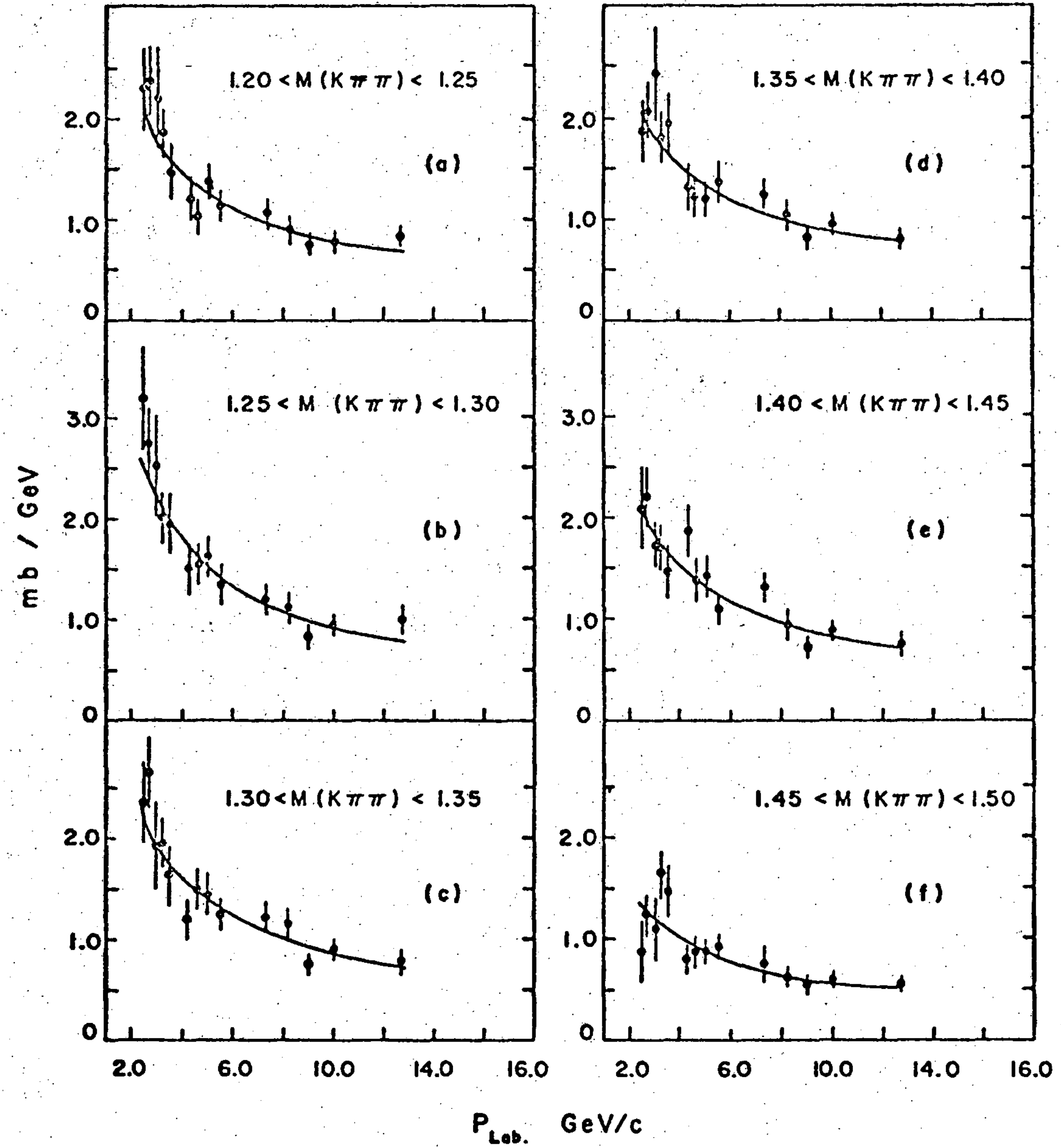


Fig. 20. Cross section for $K^+p \rightarrow Q^+p \rightarrow K^+\pi^-\pi^+p$.[37]

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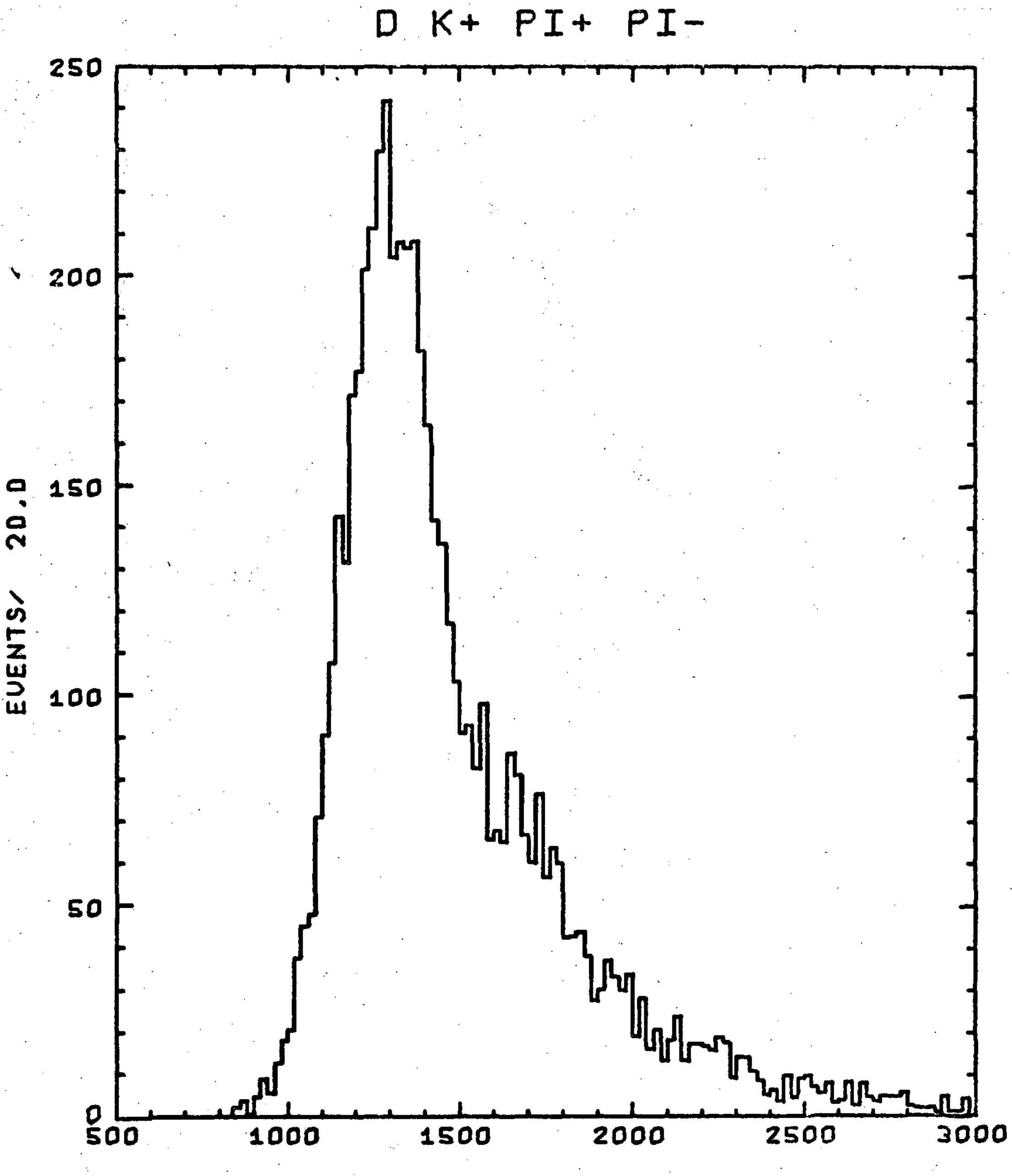

Fig. 21. $K^+\pi^-\pi^+$ spectrum from $K^+d \rightarrow K^+\pi^-\pi^+d$ at 12 GeV/c (Firestone, Ref. 40).

Pignotti[18] the qualitative successes of multi-Regge fits do not detract from these arguments.

(ii) There are theoretical arguments which suggest that mass enhancements with the property that cross sections for the production of a given fixed mass interval ΔM of the enhancement goes to a finite limit at very high incident energy are indeed resonant.[41] The data of Fig. 20, for example, suggest the Q as such a structure.

(iii) Finally I take note of the recent observations of coherent A_1 production by a large variety of nuclei ranging from beryllium to lead, and optical model analyses leading to estimates of effective "A_1" nucleon cross sections.[42] These are typical of single pion-nucleon cross sections and tend to confirm the interpretation of the A_1 as a single particle.[43]

To all this it seems essential to add some warnings. The Chew-Pignotti multiperipheral model suggests for a process such as A_1 production a $\rho\pi$ mass spectrum which looks roughly like

$$d\sigma \sim \frac{1}{s^2}\left(\frac{s}{M^2_{\rho\pi}}\right)^{2\alpha_{\mathbf{P}}} \left(M^2_{\rho\pi}\right)^{2\alpha_\pi} \frac{dM^2_{\rho\pi}}{M^2_{\rho\pi}} \sim \frac{dM^2_{\rho\pi}}{M^6_{\rho\pi}} .$$

One might therefore expect $\rho\pi$ resonant amplitudes to be highly distorted toward <u>low mass</u> by the dynamics of the process. This may explain why the mass spectrum from baryon diffraction into nucleon-pion seems to exhibit the large contributions near 1350 MeV, well below the lowest $N^*_{1/2}$ established by pion-nucleon phase-shift analysis.[44] It follows that resonance parameters obtained by simple Breit-Wigner fits to diffractive structures from three-body exclusive reactions must be treated with considerable caution.

I want to complete this lecture by apologizing to the enormous number of contributors to hadron spectroscopy whose work was neglected, misrepresented, or otherwise improperly treated in what was purported to be a "Review of Hadron Spectroscopy." With an order of magnitude increase in time (accompanied by a similar increase in the wisdom of the lecturer) one might have been able to do the subject better justice.

FOOTNOTES AND REFERENCES

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32. The Purdue-Davis-Indiana Group (Ref. 30) actually quotes a mass of 1759±10 MeV for this state. The only convincing evidence for such a precise mass determination is a fairly narrow and well-defined peak in the $K\pi\pi$ mass spectrum at this value. The LBL data, however, do not show this peak, at least with any sharpness which would match such a mass determination. Consequently I have taken a very conservative view as to our present knowledge of the parameters of this new K^*.

33. J. A. J. Mathews et al., Phys. Rev. D3, 2561 (1971). Note that for reasons unclear to this lecturer the state in question has been dubbed φ(1680). The label ω(1680) seems far more logical and hence I have adopted it in this talk.

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