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# THE $A_2$ AND THE $2^+$ NONET. CONSISTENCY OF DATA

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## ABSTRACT

New data on the $A_2^+$ meson fail to show the two-peak structure seen in the $A_2^-$ experiments of the CERN group. All the bubble chamber experiments on $A_2$ production are reviewed and the new data are compared with the CERN data. The two-parameter double-pole formula used to fit the CERN data does not appear to explain the new data. Therefore the only way to reconcile the various experiments on the charged $A_2$ is to assume the presence of two coherently produced resonances with $J^P = 2^+$, with a phase depending on either the charge of the incoming beam, or the momentum transfer to the target proton, or the incident momentum, or all three. The $K^*(1420)$ and the f meson, members of the same $2^+$ nonet as the $A_2$, do not seem to show any structure consistent with the two-parameter double-pole formula.

## I INTRODUCTION

Martin has presented the results of the CERN boson spectrometer (CBS) and the missing-mass spectrometer (MMS) experiments, both of which consistently show structure in the $A_2$ region.[1] The CBS experiment has seen structure[2]

in the $X^-$ of the reaction $\pi^- p \rightarrow pX^-$ as well as in the $K^- K^0$ decay of the $A_2^-$.[3] In this paper I review all the bubble chamber experiments on the charged $A_2$, including the new LRL data.[4] In the latter part of this paper I present the LRL group's experimental results of the search for structure in the $K^*(1420)$ meson[5] and the f meson.[6]

There are presently reports of split $A_2$ from three experiments[1,7,8] (not six as often mentioned by Maglic[9]), of which two are bubble chamber experiments. Many bubble chamber experiments[10-13] have failed to give conclusive results either way.

Figure 1 shows the results from the CERN $\pi^- p \rightarrow pX^-$ experiments.[2] The curves drawn on the data are labeled:

Two incoherent Breit-Wigner resonances (BW), $P(\chi^2) \leq 0.2\%$;

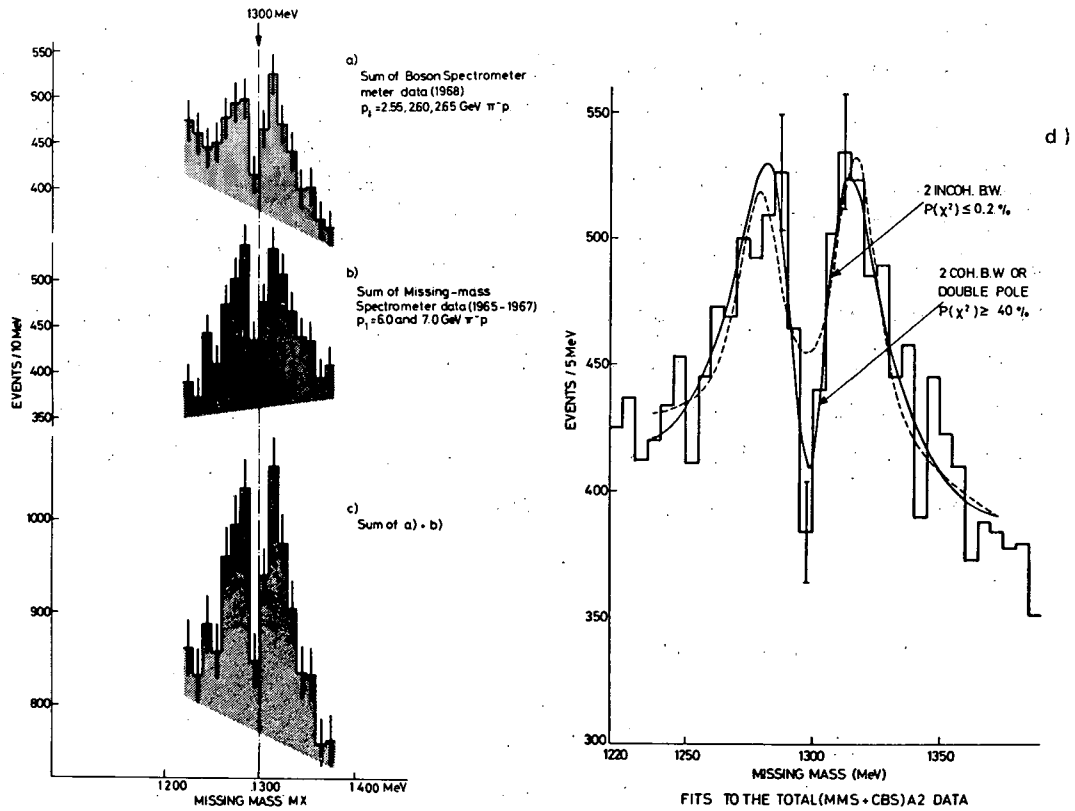


Fig. 1. (a, b, and c) Evidence for $A_2$ splitting from the reaction $\pi^- p \rightarrow p X^-$ in the two CERN experiments, (d) the same data plotted in 5-MeV bins and fitted to the various hypotheses.

Two coherent BW or double pole, $P(\chi^2) \geqslant 40\%$.

For two coherent or incoherent BW is usually meant the sum of two complex amplitudes as:

$$T = \frac{1}{\epsilon_1 - i} + e^{i\Phi} \frac{1}{\epsilon_2 - i} \tag{1}$$

where

$\Phi$ is random for two incoherent BW, i.e., $|T|^2 = |T_1|^2 + |T_2|^2$ (2)

$\Phi$ is fixed for two coherent BW, (3)

$\epsilon_i = \frac{E - M_i}{\Gamma_i/2}$ (for $i = 1, 2$), (4)

and $M_i$ and $\Gamma_i$ are mass and width of the ith resonance. The double pole formula, used in the experiments that see the split $A_2$, is

$$|T|^2 = \left[\frac{\Gamma(M - M_0)}{(M-M_0)^2 + (\Gamma/2)^2}\right]^2 . \tag{5}$$

This is a two-parameter formula; $M_0$ is the mass at which the dip occurs and $\Gamma$ is the width of the double pole (approximately equal to the distance between the two peaks). This formula[14] has been widely used, and for the one-channel case it can easily be derived by multiplying the S matrices of the two resonances,

$$S = S_1 \cdot S_2 = \left(\frac{\epsilon_1 - i}{\epsilon_1 + i}\right)\left(\frac{\epsilon_2 - i}{\epsilon_2 + i}\right),$$

then imposing $\epsilon_1 = \epsilon_2$ (that is, $M_1 = M_2 = M_0$ and $\Gamma_1 = \Gamma_2 = \Gamma_0$), and finally using $S = 1 + 2iT$. This formula produces the double peak with a large dip in the middle, as shown in Fig. 1.

This formula is strictly correct only for a one-channel case--that is, a completely elastic resonance. The $A_2$ however, decays in at least three channels, and things may get a lot more complicated. Rebbi and Slansky[15] have discussed this point and proved that in a many-channel case the shape of a double pole can be completely different: the peaks may have any relative heights, the dip may be anywhere and may even vanish, and the peaks may be double in some channels and single in others. A parameter that

measures the strength of the dipole introduced by Rebbi and Slansky is $\xi$. This parameter has values

$$0 < \xi < 1 , \tag{6}$$

and only for $\xi = 1$ can one have double peak structure in every channel and can the distributions look very much like the single-channel case.

It seems to me that the case $\xi = 1$ that every experimentalist has been using so far is only one possibility out of a continuum, and it would be unlikely that at every incident energy, every momentum transfer, and every charge of the $A_2$ should one find the same value of $\xi$.

The obvious conclusion of this discussion is that it would be nice if a two-parameter formula such as the one of Eq. (5) were sufficient to explain all the $A_2$ data, but it is somewhat unlikely that this is really the case. The experiments we will review in fact indicate that a more complicated structure than Eq. (5) is needed to explain all the data.

## II CHARGED $A_2$ EXPERIMENTS

As discussed in the preceding section, the shape of the $A_2$ can depend on the production mechanism, on the incident momentum, and on the momentum transfer. Therefore we have to take all these conditions into consideration in reviewing the experiments.

Table I is a summary of five of the experiments that have given any results on the $A_2$ splitting (or not splitting). It should be pointed out that there are in addition many bubble chamber experiments that (although with more statistics than some of the experiments listed in Table I) do not show any structure or cannot lead to any conclusion either way.[11-13]

Table II is a summary of the resonance parameters quoted in the five experiments listed in Table I.

Table I. Summary of experiments that investigated $A_2$ splitting. The reactions studied are $\pi^{\pm}p \rightarrow pA_2^{\pm}$, except for the last experiment, which is $\bar{p}p \rightarrow A_2^{\pm}\pi^{\mp}$. The columns "Events in peak" and "background/signal" have been evaluated by this author. Po stands for "possible, consistent with the data."

| Reaction | $P_{beam}$ (GeV/c) | Group | Ref. | Method | Decay mode[a] | $\Gamma_r/2$[b] (MeV) | $-t_{pp}$[c] | Events[d] in peak | Bkgd.[d]/Signal | Probability of fit: BW | Probability of fit: Double pole | Probability of fit: 2 coh. BW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\pi^-p$ | 2.6 | CERN | 2 | 0 deg | $X^-$ | 5.2 | 0.09-0.68 | 1100 | 5.3 | << 0.2% | ≥40% | ≥40% |
| | 6, 7 | CERN | 16 | Jac. peak | $X^-$ | 16 | 0.20-0.29 | 1400 | 4.0 | | | |
| | 7 | CERN | 3 | CBS | $K^-K_1$ | 10 | 0.20-0.29 | 145 | 0.34 | 1% | > 60% | Po |
| $\pi^-p$ | 6 | BNL | 10 | HBC | $\pi^-$MM | 10 | 0.22-0.39 | 100 | 1.5 | Po[e] | Po[e] | Po[e] |
| $\pi^+p$ | 7 | LRL | 4 | HBC | $\rho^0\pi^+$ | 6.4 | > 0.2[f] | 833 | 1.4 | 14% | 0.3% | Po |
| | | | | | $\eta\pi^+$ | 8.2 | all[f] | 151 | 0.23 | 13% | 0.3% | Po |
| | | | | | $K^+K_1$ | 3.6 | all[f] | 101 | 0.34 | | | |
| $\pi^+p$ | 5 | BDNP | 7 | HBC | $\rho^0\pi^+$ | 5 | t' > 0.1 | 108 | 1.3 | 20% | 63% | Po |
| $\bar{p}p$ | 0, 0.7, 1.2 | CPL | 8 | HBC | $K^{\pm}K_1$ | 5 | --- | 270 | 3.5 | 4% | 65% | Po |

a. $X^-$ stands for negative missing mass, MM stands for neutrals.
b. $\Gamma_r$ is the full width of the resolution function at half maximum.
c. $t_{pp}$ is the four-momentum transfer squared in $(GeV/c)^2$.
d. Events in peak are events above the background quoted by the authors of the various papers. Both the events in the peak and the background/signal are calculated in the region 1200 to 1400 MeV.
e. No probabilities quoted for this experiment. The fits of the first two columns were tried and the authors state that "the two-peak fit is better, although not significantly, than the one-peak fit."
f. The momentum-transfer distribution of the $A_2$, as seen in the $K^+\bar{K}^0$ and $\eta\pi^+$ channels, goes to zero rapidly; only 7% of the events have $-t > 0.7$ $(GeV/c)^2$.

Table II. Summary of parameters quoted by the five groups that have investigated the $A_2$ splitting.

| Experiment | Decay mode | Single resonance M | Single resonance Γ | Single resonance $P(\chi^2)$ | Double pole (Eq. 5) M | Double pole (Eq. 5) Γ | Double pole (Eq. 5) $P(\chi^2)$ | Positions of peaks[a] $A_{2L}$ | Positions of peaks[a] $A_{2H}$ |
|---|---|---|---|---|---|---|---|---|---|
| CERN | $X^-$ | --- | --- | --- | 1298 ±5 | 28 ±5 | 40% | 1278 ±5 | 1318 ±5 |
| | $K^-K_1$ | --- | --- | --- | 1300 ±5 | 32 ±5 | 60% | 1276 ±6 | 1323 ±6 |
| BNL[b] | $\pi^-MM$ | 1287 ±10 | 94 +30 -20 | | --- | --- | --- | 1269 ±5 | 1315 ±5 |
| LRL[c] | $\rho^0\pi^+$ | 1304 ±5 | 82 ±13 | 14% | 1298 ±4 | 21 ±4 | 0.3% | --- | --- |
| | $K^+K_1+\eta\pi^+$ | 1309 ±6 | 100 ±15 | 13% | 1305 ±4 | 30 ±4 | 0.3% | --- | --- |
| BDNP | $\rho^0\pi^+$ | 1308 ±12 | 139 ±50 | 20% | 1306 ±4 | 41 ±5 | 63% | 1275 ±6 | 1338 ±4 |
| CPL | $K^\pm K_1$ | 1296 ±7 | 124 +41 -27 | 4% | 1303 ±2 | 31 ±4 | 65% | 1281 ±3 | 1325 ±3 |

a. Values quoted here are results of fits assuming two incoherent Breit-Wigner resonances.
b. See footnote (e) of Table I; single-resonance and two-resonance fits both give good probability.
c. The probabilities quoted for this experiment are calculated in the region 1200 to 1400 MeV.

## A. $\pi^-p$ EXPERIMENTS

CERN experiment. The first experiment to show a double-pole-like structure was the MMS experiment in 1966, included in ref. 2. Figure 1 shows all of the CERN data for the reaction

$$\pi^-p \rightarrow pX^-$$

The momenta studied were 2.55, 2.60, and 2.65 GeV/c in the CBS experiment and 6.0 and 7.0 GeV/c in the MMS experiment. At the first Philadelphia Conference Kienzle[16] reviewed these data; since

then various groups have been searching for an effect as dramatic as that shown in Fig. 1.

The CERN group found the same effect again in their $K^-K_1$ mass distribution shown in Fig. 2. This experiment, too, is described by Martin,[1] to whom we refer for details. Table I contains a summary of the characteristics of this experiment: the resolution, the momentum-transfer region, the size of the signal, and the probabilities for various fits. Table II shows the values of the parameters obtained by fitting the data to various hypotheses, and Table III shows the details of the fits to the data of Fig. 1d. It is interesting to notice that the two-coherent-resonances hypothesis has two solutions equally good: (a) a symmetric solution, i.e., two narrow resonances, (b) a broad-narrow solution, i.e., a wide resonance and a narrow one with the same mass. We will come back to this point later.

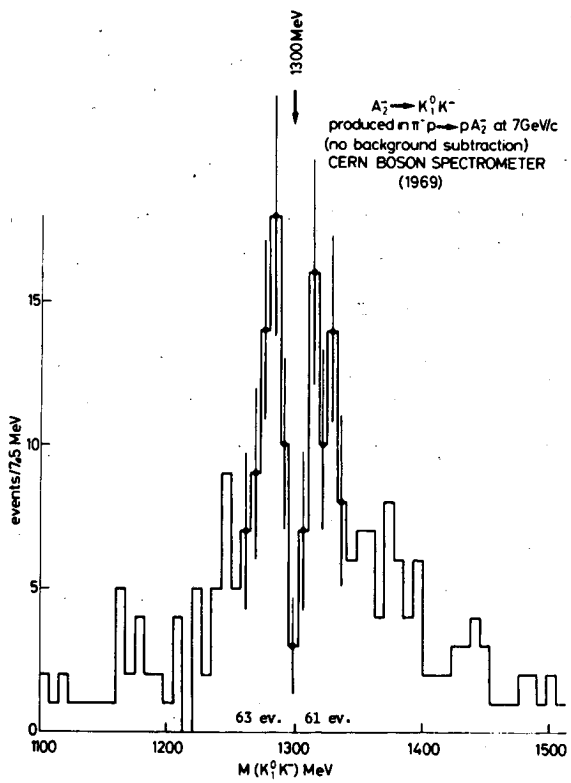


Fig. 2. The $K^-K_1$ decay mode of the $A_2^-$ as seen by the CERN (CBS) experiment at 7 GeV/c.

Table III. Results of various fits to the $A_2$ data in the reaction $\pi^- p \rightarrow pX^-$ done by the CERN group.[2]

Double peak fits to the total (MMS + CBS) split $A_2$
(Uncertainty in mass $\Delta M = \pm 5$ MeV; in width $\Delta\Gamma = \pm 5$ MeV)

| Hypothesis \ Parameters | $M_1$ $\Gamma_1$ | $M_2$ $\Gamma_2$ | $P(\chi^2)$ |
|---|---|---|---|
| 2 incoherent B.W. | 1278 22 | 1318 21 | $\leq$0.2% |
| 2 coherent B.W. sym. solution | 1289 22 | 1309 22 | $\geq$ 40% |
| asym. solution (broad-narrow) | 1298 90 | 1297 12 | $\geq$ 40% |
| "Double Pole" | 1298 28 | | $\geq$ 40% |

BNL experiment. Crennell et al.[10] have looked at the reaction

$$\pi^- p \rightarrow p\,\pi^- MM \qquad \text{at } 6.0 \text{ GeV/c.}$$

Their best resolution region is for proton momenta between 0.485 and 0.660 GeV/c, corresponding to the momentum transfer region reported in Table I. The $\pi^-$MM plot for this region is shown in Fig. 3. There are 100 events above 150 background events. The values of the parameters for the various fits are shown in Table II; however, the authors do not quote $\chi^2$ probabilities and state "The two-peak fit is better, although not significantly, than the one-peak fit." So we take these data as not giving evidence either way. No additional information from the $K^-K^0$ or the $\eta\pi^-$ (with $\eta$ decaying into $\pi^+\pi^-\pi^0$) decays of the $A_2$ is available from this experiment.

## B. $\pi^+p$ EXPERIMENTS

LRL experiment.[4] This is the bubble chamber experiment with the largest statistics. The reactions studied at 7 GeV/c are

$$\pi^+p \rightarrow p\,A_2^+, \qquad A_2^+ \rightarrow K^+K_1 \quad (133), \tag{7a}$$
$$A_2^+ \rightarrow \eta\pi^+ \quad (185), \tag{7b}$$
$$A_2^+ \rightarrow \rho^0\pi^+ \quad (1988), \tag{7c}$$

where the number in parentheses indicates the total number of events in the 1200- to 1400-MeV region for each of the three reactions. For reactions (7b) and (7c) the events in the $\Delta^{++}$ band ($M_{\pi^+p} < 1.38$ GeV) have been removed from the sample in order to reduce the background. The $K^+K_1$ and $\eta\pi^+$ signal are for the first time seen clearly and with large statistics in a bubble chamber experiment, as shown in Fig. 4a and 4c. For the $\rho^0\pi^+$ decay an additional cut was made, i.e., only events with momentum

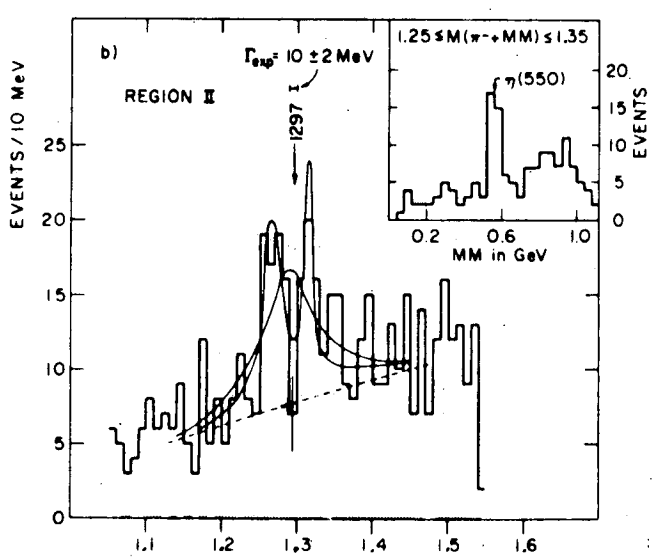


Fig. 3. The data of Crennell et al. (Ref. 10) for the reaction $\pi^-p \rightarrow p\pi^-MM$ at 6 GeV/c when the condition $0.485 < P_p < 0.660$ GeV/c was imposed. The insert shows the MM distribution. The curves correspond to a single-Breit-Wigner (BW) resonance fit and to two-incoherent-BW fit. Both hypotheses fit reasonably well, although the two-peak hypothesis fits better.

transfer $-t > 0.2$ $(GeV/c)^2$ have been included. This cut was imposed in order to reduce the background coming from the low $\rho\pi$ mass enhancement due to diffraction scattering (usually called diffractive $A_1$ production). For $-t > 0.2$ the $A_2$ signal (Fig. 4c) stands above an almost flat background. In Fig. 4c the $\pi^+\pi^-\pi^+$ invariant mass is shown instead of the $\rho^0\pi^+$ in order to avoid distortion of phase space due to the well-known crossing bands effect.[17] In fact, at the $A_2$ mass most of the Dalitz plot is still covered with $\rho$. From the Dalitz plot of the $A_2$ region (1200–1400 MeV), it is estimated that 90% of the events of Fig. 4c in the $A_2$ region are $\rho^0$ events.

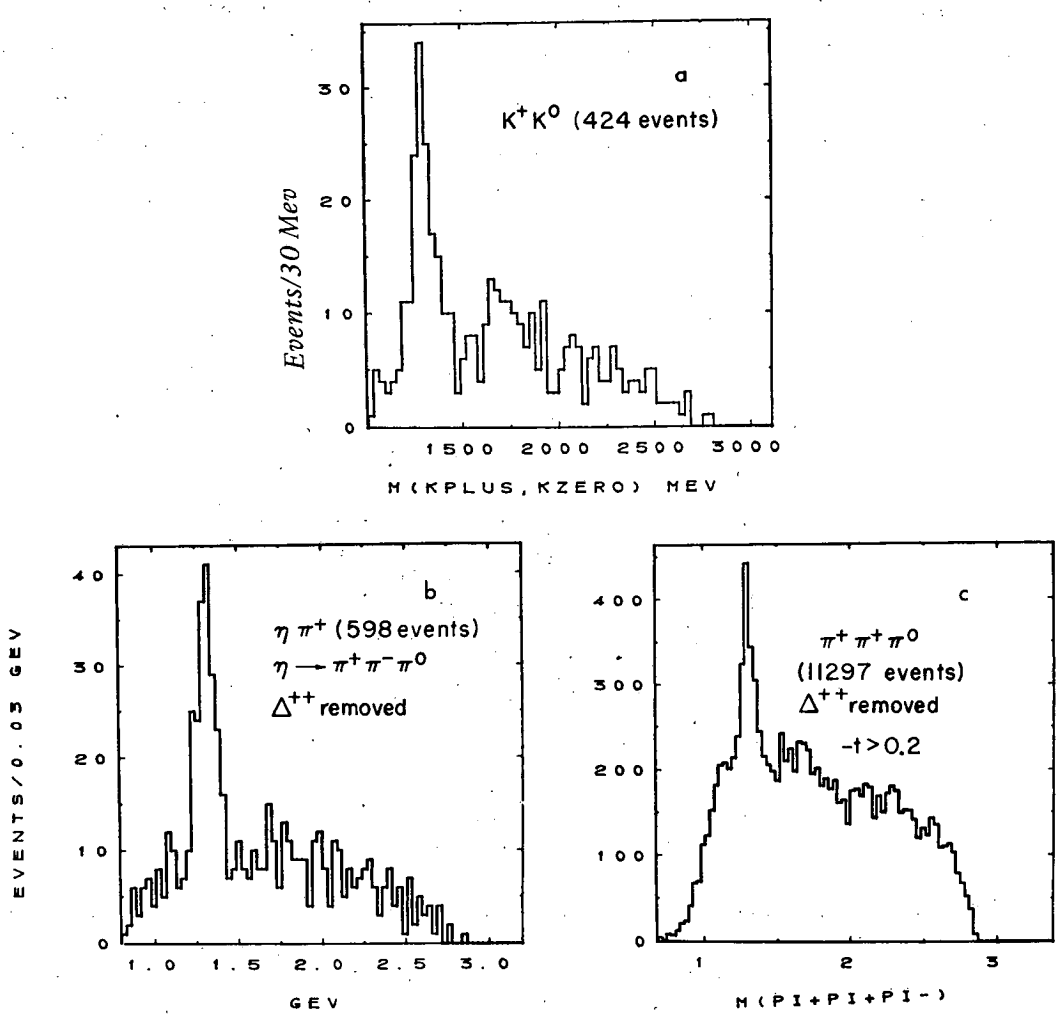


Fig. 4. Results of the LRL experiment at 7 GeV/c. Mass plots for (a) $K^+K_1$, (b) $\eta\pi^+$, (c) $\pi^+\pi^-\pi^+$.

The resolution of this experiment is very good; as seen from Table I, it is 3.6 MeV for the $K^+K_1$ channel and goes up to 8.2 MeV for the $\eta\pi^+$ channel. Figure 5 shows the $\eta$ signal for the events of Fig. 4b. The curve drawn on it is the calculated resolution, which agrees very well with the histogram, which is in fact the measured resolution. This is only one of the many tests done to check the resolution (we refer the reader to Ref. 4 for more details).

Figure 6 and 7 show the fit of the two hypotheses (BW and the double pole of Eq. 5) to the data. Figure 6 shows the $\rho^0\pi^+$ data and Fig. 7 the $K^+K_1$ and $\eta\pi^+$ data together. The results of the fits are given in Tables I and II. The double-pole fit is bad in both samples; its probability with respect to the one resonance hypothesis in the region 1200 to 1400 MeV is 0.16% and 0.18% for

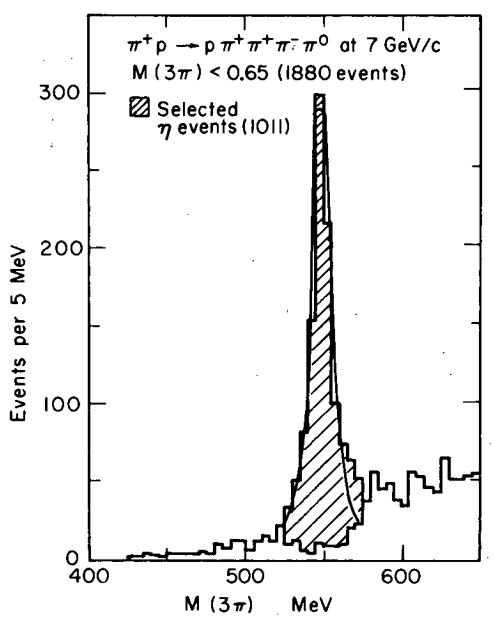


Fig. 5. The $\eta$ signal in the LRL data at 7.0 GeV/c. Shaded area shows $\eta$ events selected for the plot of Fig. 4b by fitting the events to $\pi^+p \to p\pi^+\eta$ and then fitting the decay $\eta \to \pi^+\pi^-\pi^0$.[4] Curve drawn on histogram is the calculated resolution. ($\Gamma_r/2$ = 6.2 MeV)

Figs. 6 and 7 respectively calculated by evaluating the ratio of the likelihoods of the fits. In each case the appropriate mass resolution has been folded in with the matrix element form.

It should be pointed out here that these probabilities depend on the mass interval that has been fitted. For a smaller mass interval the background can be badly estimated; although the fit in the resonance region might be better, it might not represent the real situation. The background was fitted over the region shown in Figs. 6 and 7.

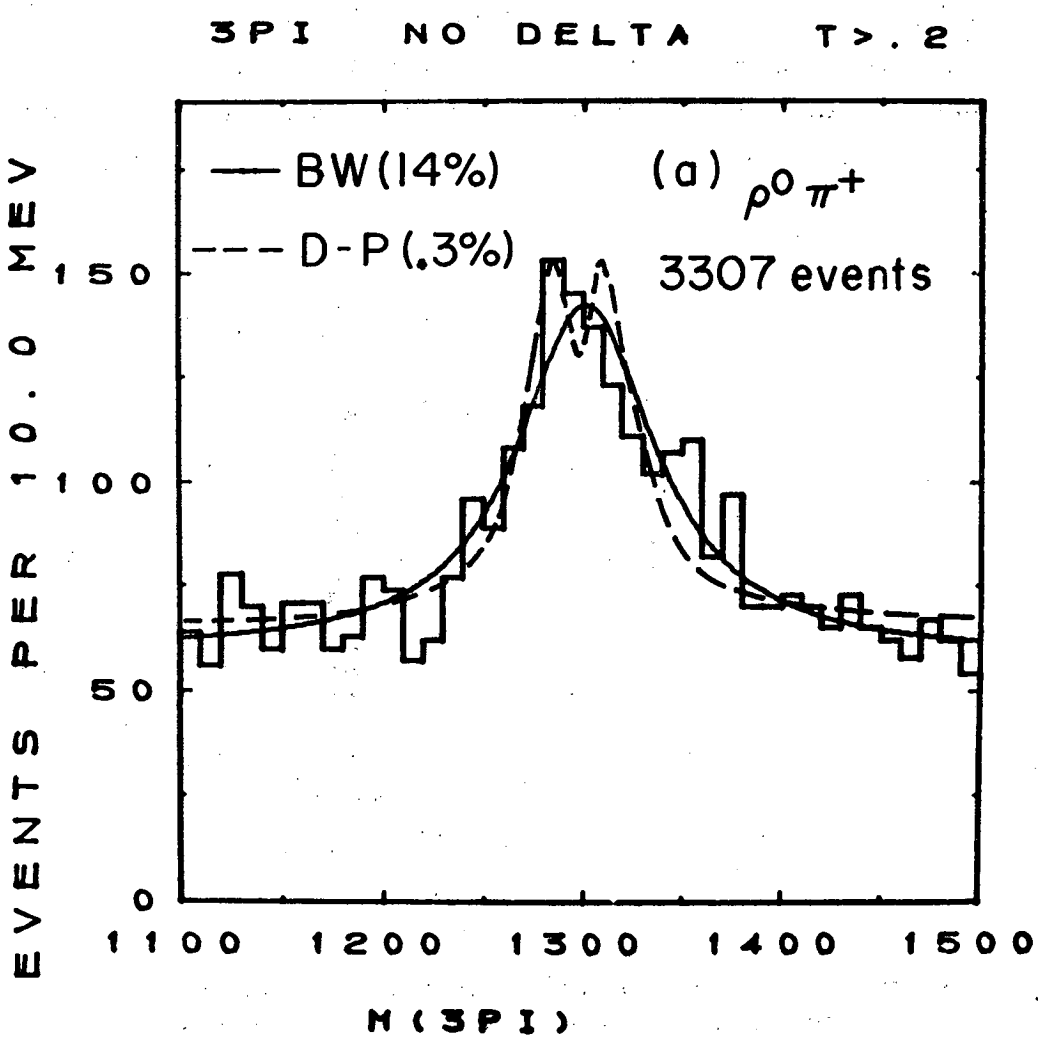


Fig. 6. Fits to the LRL data (Ref. 4) for the $\rho^0\pi^+$ decay of the $A_2$. Solid line is best fit obtained for a BW resonance, dashed line is the best fit for the double-pole hypothesis (Eq. 5).

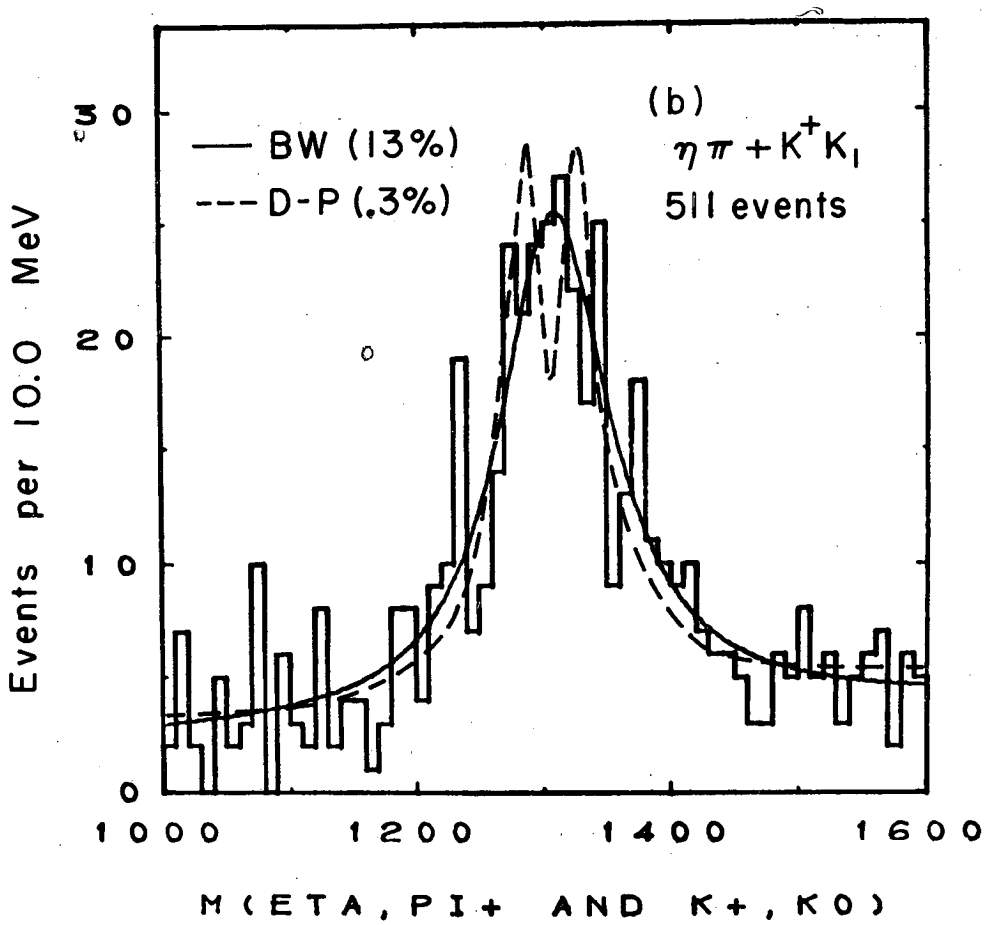


Fig. 7. Fits to the LRL data (Ref. 4) for the $K^+K_1$ and $\eta\pi^+$ decays of the $A_2$. Solid line is best fit obtained for a BW resonance, dashed line is the best fit for the double-pole hypothesis (Eq. 5).

Various fits were tried for two coherent BW's, and since no separate peaks are present in the data, the values of the two masses, if left free, tend to fall at the same place. Fits using the CERN parameters of Table III and letting the relative heights of the two resonances as well as the phases vary, give a reasonably good $\chi^2$. However, these data need only one BW and cannot give any results on the two-coherent-resonances hypothesis other than that it is compatible with the data.

The BDNPT experiment.[7] The 5-GeV/c experiment of Böckman et al. shows some structure in the $\rho^0\pi^+$ data when the $(t-t_{min}) < 0.1$ cut is made. Figure 8 shows the data. An inspection of Table I and Fig. 6 shows that the data of this experiment are about 1/8 of the LRL experiment. The probabilities, shown in the caption, for the resonance fit and the double-pole fit are almost equally good, so I would say the evidence for a split $A_2$ from this experiment is weak. The fit for two incoherent BW's gave 70% probability, with the masses quoted in Table II and widths $\Gamma_1 = 27 \pm 13$, $\Gamma_2 = 17 \pm 15$ MeV.

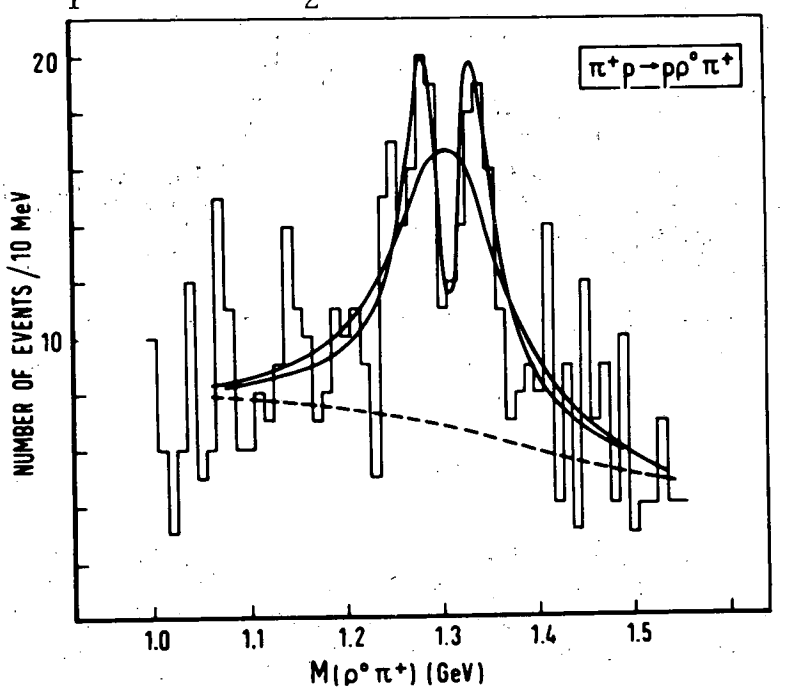


Fig. 8. Data of Böckman et al. (Ref. 7) at 5.0 GeV/c. The two curves correspond to one BW fit (smooth curve, 20% probability) and to a double-pole fit (Eq. 5, 63% probability).

## C. INCIDENT BEAMS OTHER THAN PIONS

The $\bar{p}p$ experiment of Aguilar-Benitez et al.[8] shows structure in the $K^{\pm}K_1$ mass plot, as shown in Fig. 9. The results of the fits

to these data favor the double-pole hypothesis. Again Eq. (5) has been used, and the results are shown in Tables I and II. The fit for two incoherent BW's gives a 28% probability with the masses reported in Table II and widths of $22^{+10}_{-7}$ MeV for both, It seems to me that this is the only experiment that supports the split $A_2$ hypothesis of the CERN experiments.

In addition to the $\bar{p}p$ experiment, another observation of charged $A_2$ in a non-pion beam has been reported by Crennell et al.[18] The reaction studied was $K^- n \rightarrow \Lambda \rho^0 \pi^-$, and a narrow peak ($\Gamma \approx 40$ MeV) at a mass of 1289 ± 10 MeV was observed. I do not include this observation in this discussion for two reasons: (a) It is a completely different reaction with different production mechanism. (b) The statistics involved in the experiment

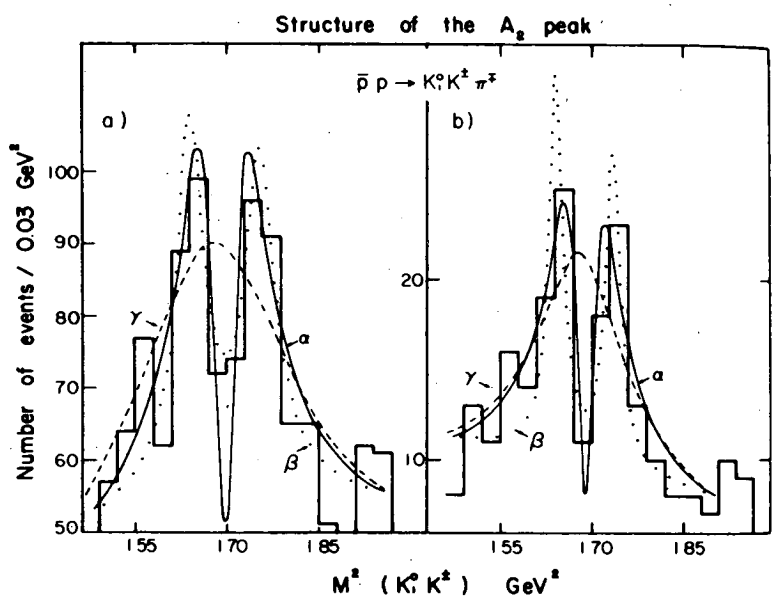


Fig. 9. Data of Aguilar-Benitez et al. (Ref. 8): (a) all antiproton momenta included (0, 0.7, 1.2 GeV/c), note the suppressed scale in this plot; (b) the 0.7 GeV/c data only. The curves correspond to the various hypotheses: ($\alpha$) double-pole (65%), ($\beta$) incoherent sum of two BW's (28%), and ($\gamma$) single BW (4%). Percentages in parentheses refer to plot (a).

are less than any of the experiments discussed so far; the effect is at most 40 events on a background of 60 events.

## III COMPARISON OF CHARGED $A_2$ DATA

The two experiments that can be directly compared are the CERN and LRL experiments, because they both use a pion incident beam and have the largest statistics. As shown in Table I, apart from the fact that the charge of the incident beam is different, the other major difference, that has been argued about during this Conference, is in the momentum transfer detected by the two experiments. Let me try to make some comparisons. Table IV is a summary of these comparisons.

Table IV. Comparison of the CERN (Ref. 1) and LRL (Ref. 4) experiments on charged $A_2$ production in the reactions $\pi^{\pm}p \rightarrow p\,A_2^{\mp}$. $P_p$ is the momentum of the proton in the laboratory system; $-t_{pp}$ is the four-momentum transfer squared to the proton.

| | Experiment | Beam | $P_\pi$ (GeV/c) | Decay | $P_p$ (GeV/c) | $-t_{pp}$ $(GeV/c)^2$ | Events[a] in peak | Background[a] | Comments |
|---|---|---|---|---|---|---|---|---|---|
| Same $P_\pi$ | CERN | $\pi^-$ | 6,7 | $X^-$ | 0.46-0.56 | 0.20-0.29 | 1400 | 5660 | split $A_2$ |
| | LRL | $\pi^+$ | 7 | $\rho^0\pi^+$ | >0.32 | >0.10 | 1132 | 1943 | smooth $A_2$ |
| Same $P_\pi$, t | LRL | $\pi^+$ | 7 | $\rho^0\pi^+$ | 0.46-0.56 | 0.20-0.29 | 273 | 497 | smooth $A_2$ |
| $K^{\pm}\overline{K}^0$ | CERN | $\pi^-$ | 7 | $K^-K^0$ | 0.46-0.56 | 0.20-0.29 | 145 | 50 | split $A_2$ |
| | LRL | $\pi^+$ | 7 | $K^+\overline{K}^0$ | all | all | 101 | 34 | smooth $A_2$ |

a. Events in the region 1200-1400 MeV.

*Same incident momentum.* The MSS experiment was done at 6 and at 7 GeV/c, the LRL one at 7 GeV/c. Figure 10 shows the comparison of these two experiments which were done at similar incident momentum. Notice that the number of events in the peak is somewhat comparable, although, since the CERN apparatus detects only the proton in the final state, their background is much worse. This plot shows that for a given incident momentum the CERN and LRL data are different, therefore

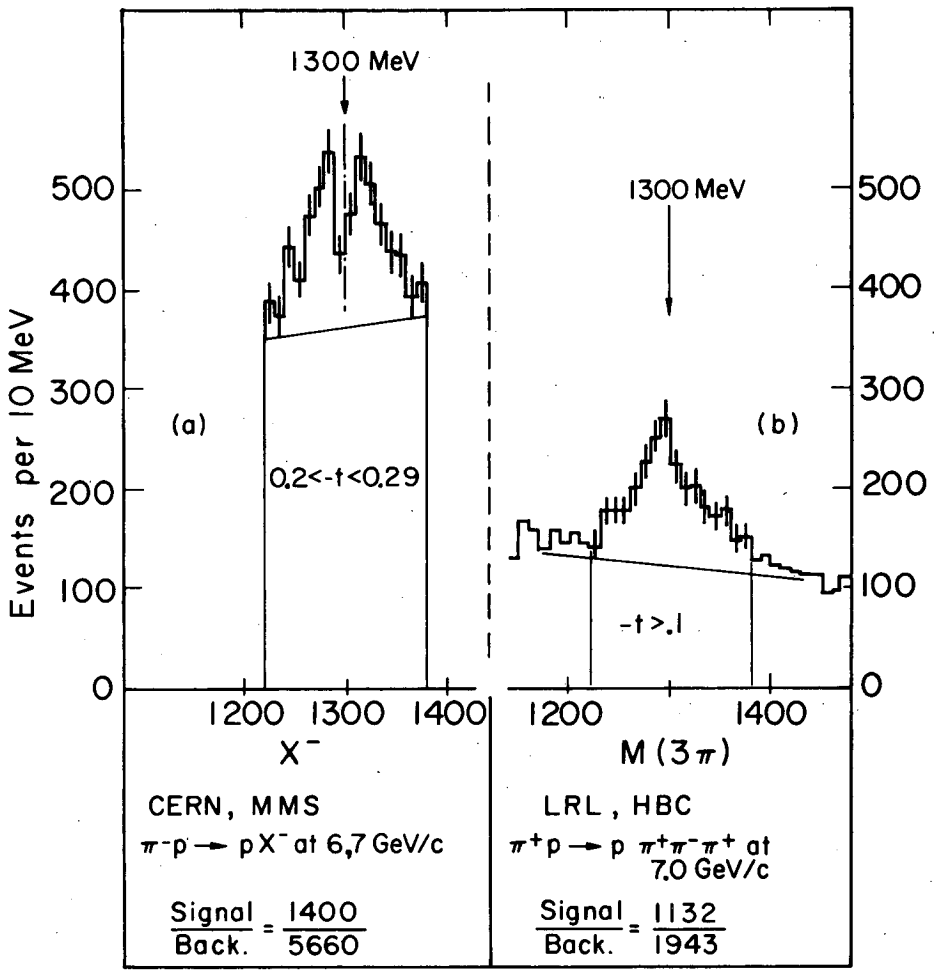


Fig. 10. Comparison of CERN and LRL data at the same incident pion momentum. (a) CERN data (resolution $\Gamma_r/2$ = 8 MeV), (b) LRL data ($\Gamma_r/2$ = 6.4 MeV).

the splitting of the $A_2$ depends upon some other variable, the incident momentum alone does not seem to explain the effect. As shown in Table IV the CERN data were taken in a small momentum transfer region, the LRL data include all momentum transfers. Calling $t_C$ the momentum transfer of the CERN experiment, the LRL data shows a ratio of events below/$t_C$/ above equal to 1.5/1/2.

*Same incident momentum, same t.* The statistics of the LRL data get small if the same t cuts as CERN are required. The LRL data with the same t cuts as CERN are shown in Fig. 11. There

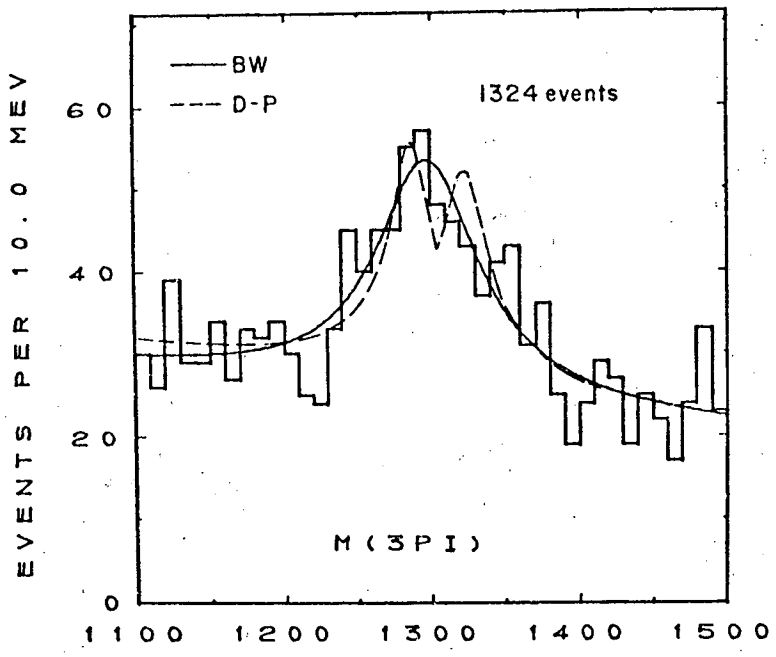


Fig. 11. The $3\pi$ mass plot of the LRL experiment for momentum transfer cut as for the CERN experiment at the same energy ($0.20 < -t < 0.29$). $\Delta^{++}$ events have been removed.

are 770 events in the region 1200 to 1400 MeV and no splitting is evident. However, the same is not sufficient to discriminate between the two hypotheses, the likelihood ratio of D-P over BW being 16%.

*Conclusions.* The CERN CBS data at 2.6 GeV/c in Fig. 1a shows structure at the same place as the 7 GeV/c data, therefore the splitting does not seem to depend upon the incident momentum. The experiment, however, was done in about the same momentum transfer region as the MMS experiment, whereas the LRL experiment was done overall values of t, so it is possible that the splitting depends upon the value of t. If we accept the data of Fig. 11 as evidence against the double-pole an attractive possibility is a dependence on the charge of the incident pion. This hypothesis would still explain why the two CERN experiments done at similar values of t but at different incident momentum show the same structure.

This last hypothesis is discussed further in Section 6.

*Comparison of $K^{\pm} K_1'$ data.* Figure 12 includes the CERN and LRL data for the $K^{\pm} K_1$ decay mode plotted in 7.5-MeV bins. One question often asked is: are these histograms consistent with each other? In order not to wash out the differences we compare them in a restricted region, where the disagreement shows the most, that is the nine bins centered around 1300 MeV from M = 1265 MeV to M = 1332.5 MeV. The formula used is[19]

$$\chi^2 = \sum_i \frac{(A_i R - B_i)^2}{A_i R + B_i R}$$

where $A_i$ is the number of events in the ith bin of the LRL histogram, $B_i$ is the number of events in the corresponding bin of the CERN histogram, and R is $\sum_i B_i / \sum_i A_i$ (R = 100/68 = 1.47). The $\chi^2$ obtained is $\chi^2$ = 17.7 for nine degrees of freedom, which corresponds to a probability of less than 5%.

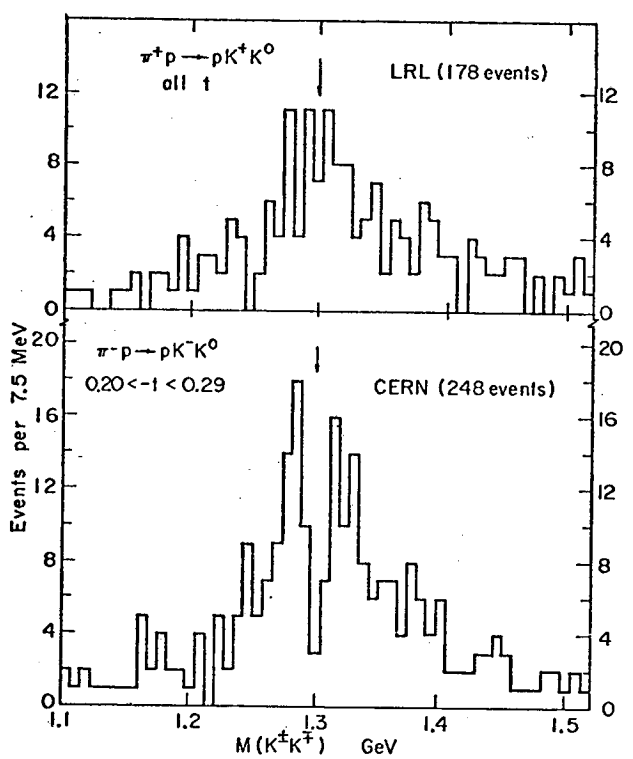


Fig. 12. Comparison of CERN and LRL data in the $K^{\pm} K_1$ decay mode. (a) LRL data ($\Gamma_r/2$ = 3.6 MeV), (b) CERN data ($\Gamma_r/2$ = 10 MeV).

## IV NEUTRAL $A_2$

The neutral $A_2$ has been so far studied in the reactions

$$\pi^- p \rightarrow n K_1 K_1, \tag{8}$$

$$\pi^+ p \rightarrow \Delta^{++} A_2^0. \tag{9}$$

In both reactions the f meson can be produced along with the $A_2$, and, since they have the same quantum numbers, interference effects may confuse the situation. However, in reaction (9) the decay mode $A_2 \rightarrow \pi^+\pi^-\pi^0$ is free from f interference.

Crennell et al.[10] studied reaction (8) at 6 GeV/c and reported a very narrow peak ($\Gamma = 20^{+16}_{-6}$ MeV) at a mass of 1311 ± 5 MeV. It is not clear what is being seen here because the width is so narrow (for f $\Gamma$ = 150 ± 25 MeV, for $A_2^0$ $\Gamma$ = 89 ± 4 MeV).[13] The claim that this narrow peak corresponds to the $A_{2H}$ and that, because of it, the two halves of the $A_2$ have different $J^P$ assignments is now disproved by the CPL data,[8] the CERN data,[3] and the LRL data.[4] This narrow peak still remains to be explained; it may be caused by some peculiar interference of f and $A_2$, or just poor statistics (only 25 events in this peak).

Beush et al.,[20] on the other hand, studied the same reaction at 5, 7, and 12 GeV/c incident $\pi^-$ with large statistics, and found a broad peak of ≈ 140 MeV which they fit by adding incoherently f and $A_2$.

These two experiments are clearly in contradiction, and do not shed much light on the $A_2$ meson.

Studies of reaction (9) have failed[7] to show any splitting in $A_2^0 \rightarrow \pi^+\pi^-\pi^0$, but the quoted resolution ($\Gamma_r/2$ = 10 MeV) is clearly worse than in the charged case. As for the decay into $K^+K^-$ or $K_1K_1$, the statistics available so far are insufficient for any conclusions. It should be mentioned here that the total width

of the $A_2^0$ signal in this reaction is consistent with the width of the charged $A_2$.[7, 13]

## V SPIN AND PARITY OF $A_2$

Kruse has summarized at this Conference[21] the results of the various spin analyses of the $A_2$ region. The data on the charged $A_2$ have been analyzed as a whole or in two parts and the $J^P = 2^+$ assignment is now established for the whole region. Both the CERN[1] and LRL experiments[22] have studied the $A_2 \to \rho\pi$ decay mode and have conclusive evidence for the $J^P = 2^+$ assignments for both halves.

The $K^+K_1$ and $\eta\pi^+$ data of the LRL group[22] show very clearly that $J^P = 2^+$ is the most likely assignment, as does the $\eta\pi$ compilation that Kruse showed at this Conference. We therefore assume that if the $A_2$ is split, both states have $J^P = 2^+$.

## VI CONCLUSIONS ON $A_2$ SPLITTING

From all the detailed discussion of the preceding sections, and assuming that none of the crucial experiments is wrong, my conclusions on the $A_2$ splitting can be summarized as follows:

1. Of the many experiments discussed only three have conclusive results. These are: (a) the CERN experiments, which consistently show a double-pole structure in $A_2^-$ decaying into $K^-K^0$, $MM^-$ and $\eta\pi^-$ (with poor statistics in the $\eta\pi^-$ channel).[1] (b) The LRL experiment,[4] which consistently shows no structure in $A_2^+$, decaying into $\rho^0\pi^+$, $K^+K_1$, and $\eta\pi^+$. (c) The $\bar{p}p$ experiment of the CPL collaboration,[8] which shows splitting in $A_2^\pm \to K^\pm K_1$. In addition there are many other bubble chamber experiments, which do not show any evidence either way.[7, 10-13]

2. The data on the neutral $A_2$ do not help in understanding the situation.

3. Spin analyses of $A_2^{\pm}$ into all three channels $\rho^0\pi^{\pm}$, $\eta\pi^{\pm}$, $K^+K_1$ definitely prefer the $J^P = 2^+$ assignment for the overall $A_2$ enhancement and for the two halves analyzed separately (for both $\rho^0\pi^+$ and $\rho^0\pi^-$ decays).[1, 21, 22]

4. The LRL experiment indicates that the two-parameter double-pole formula of Eq. (5) does not fit the data. A more general double-pole formalism, as discussed by Rebbi and Slansky,[15] should therefore be adopted. This corresponds to fitting the data with two coherently produced resonances, as already done by the CERN group.[2]

5. Comparison of the CERN and LRL experiments, which both use pion beams, shows that at the present time the splitting of the $A_2$ peak does not seem to depend on the incident beam momentum whereas it may depend on the momentum transfer. A dependence on charge of the incident beam alone, however, could probably explain the effect.

A model that has been very popular in the corridors at this Conference and that will be discussed in Sutherland's review talk originates from the analogy with the $\rho$-$\omega$ interference model of Goldhaber et al.[23] In this model two $2^+$ mesons would be produced, one mostly coupled to $\rho$ exchange, the other mostly coupled to f exchange. Since $\rho$ and f have different isotopic spin, the two amplitudes would add in the $\pi^+$ case and subtract in the $\pi^-$ case. Of course, the detailed prediction of this model should be worked out and checked with the experiments.

Another model, suggested by Arnold and Uretsky,[24] considers the possibility that one of the $A_2$'s is an exotic resonance, that is, an isospin 2 state. The two states would mix by virtue of electromagnetic interactions.

In conclusion, it seems to me that the double-pole structure of Eq. (5) should be abandoned and that models which predict two interfering resonances are more likely to explain all the data. To check the possible models, however, may require a lot more experiments at different incident momenta, different momentum

transfers, and different incident beams--that is, a lot more time and effort on the part of the experimental physicists.

## VIII $K^*(1420)$ AND f(1270). ANY STRUCTURE?

If the $A_2$ is really two states, one would expect that the other members of the nonet also show some structure. The LRL group has investigated $K^*(1420)$ and f(1270). No double-pole structure such as Eq. (5) has been detected so far in either of these two states.

A. $K^*(1420)$. Davis et al.[5] have investigated the reaction

$$K^+p \rightarrow K^+\pi^-\pi^+p \text{ at 12 GeV/c.}$$

All together 27 000 events of this type have been analyzed, of which 5665 events fall in the mass interval 1200 to 1640 MeV. The resolution is 6.5 MeV. Figure 13 shows all the data for the above reaction and the $K^*(1420)$ region alone. The BW fit is very good, whereas the two-parameter D-P of Eq. (5) has a confidence level of < 1%. These results are summarized in Table V.

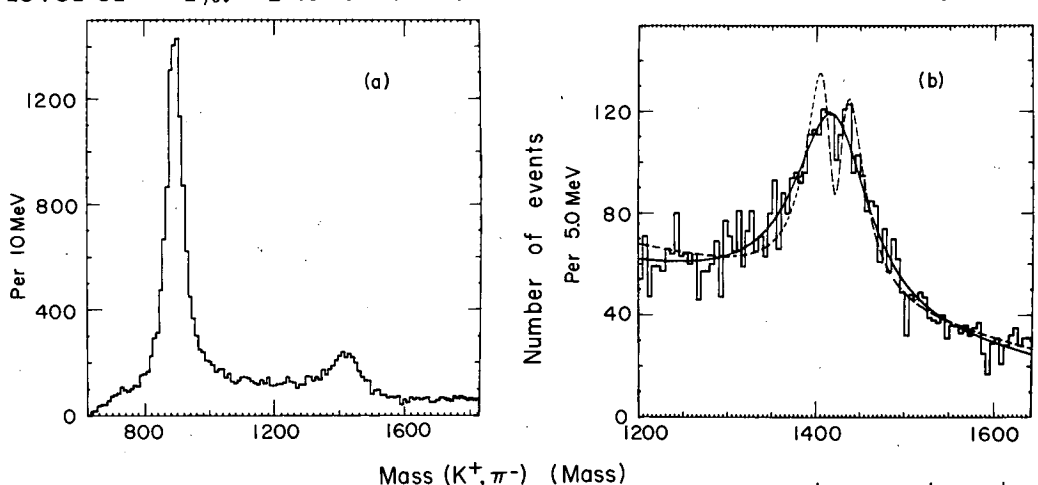


Fig. 13. (a) Sample of 27 000 events of the type $K^+p \rightarrow K^+\pi^-\pi^+p$ at 12 GeV/c studied by Davis et al. (Ref. 5) (b) The $K^*(1420)$ region: —— BW fit (47%), --- D-P fit (< 1%).

Table V. Fits to the $K^*(1420)$ and f(1270) events.

| | Total events | Events in resonance | $\Gamma_r/2$ | M | $\Gamma$ | BW | D-P |
|---|---|---|---|---|---|---|---|
| $K^*(1420)$, 1320-1520 | 5665 | 2200 | 6.5 | 1421 ± 3 | 101 ± 10 | 47% | < 1% |
| f(1270), 1000-1600 | 9307 | 4150 | 8.3 | 1472 ± 5 | 180 ± 15 | 71% | < 0.01% |

B. f(1270). The LRL group[22] has investigated f production in the reaction

$$\pi^+ p \rightarrow \Delta^{++} \pi^+ \pi^- \text{ (30740 events)}$$

at 7 GeV/c incident momentum (see Fig. 14). In the region 1000 to 1600 MeV there are 9307 events which have been fitted to the BW and to the D-P formula of Eq. (5). Here the resolution is $\Gamma_r/2$ = 8.3 MeV.

Again a D-P formula such as Eq. (5) fits very badly.

None of these two states has been fitted with a two-interfering resonance hypothesis. It is probably not difficult here to find parameters for the two resonances and a phase such

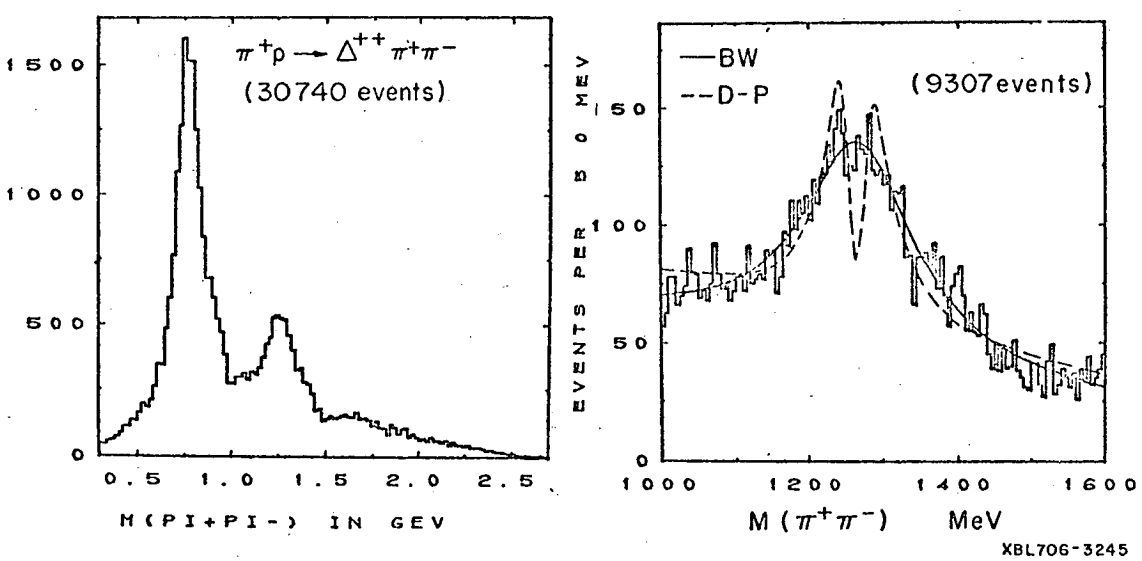


Fig. 14. (a) The 30 740 events of the reaction $\pi^+ p \rightarrow \Delta^{++}\pi^+\pi^-$ 7 GeV/c (LRL data). (b) Fits to the f region: — BW (71%), --- D-P (< 0.01%).

that a good fit is obtained. Here again the conclusion is that the two-parameter formula of Eq. (5) does not fit the data.

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## REFERENCES

1. The CERN Boston Spectrometer Group, Decay Analysis of $A_2^L$ and $A_2^H$ in the channels $A_2^- \to K_1^0 K^-$, $A_2^- \to \rho^0 \pi^-$, $A_2^- \to \eta\pi^-$, presented at this Conference by M. Martin.
2. H. Benz et al., Phys. Letters 28B, 233 (1968), includes data from the MMS and the CBS.
3. R. Baud et al., Phys. Letters 31B, 397 (1970).
4. A. Barbaro-Galtieri, S. E. Derenzo, S. M. Flatté, J. H. Friedman, M. A. Garnjost, G. R. Lynch, M. S. Rabin, F. T. Solmitz, F. Buhl, L. Epperson, S. Protopopescu, R. Ott, Production of $A_2$ Mesons at 7 GeV/c, to be published.
5. P. J. Davis, S. E. Derenzo, S. M. Flatté, M. A. Garnjost, G. R. Lynch, and F. T. Solmitz, Phys. Rev. Letters 23, 1071 (1969).
6. Lawrence Radiation Laboratory, Group A, same authors as Ref. 4, Spin-Parity Analysis of $A_2$ Mesons, to be published.
7. K. Böckman et al., Bonn-Durham-Nijmegen-Paris (E. P.) - Torino Collaboration, Nucl. Phys. B16, 221 (1970).
8. M. Aguilar-Benitez et al., CERN-Paris (C. D. F.)-Liverpool Collaboration, Phys. Letters 29B, 62 (1969).
9. Maglic's source of this erroneous information is probably his own review talk in Proceedings of the Lund International Conference on Elementary Particles, Lund, Sweden, June 1969 (Berlinska Boktrycheriet, Lund, Sweden,

1969) p. 269. There, the references are somewhat confused in fact he counts the experiments of the CERN group three times, twice as bubble chamber experiments. The other experiment he includes is our Ref. 10 below.

10. D. J. Crennell, U. Karshow, K. W. Lai, J. M. Scarr, and I. O. Skillicorn, Phys. Rev. Letters 20, 1318 (1968). The two-peak fit for this experiment is better, but not significantly, than the one-peak fit.
11. D. H. Coyne, G. S. Abrams, W. R. Butler, G. Goldhaber, B. H. Hall, J. MacNaughton, and G. H. Trilling, Bull. Am. Phys. Soc. 15, 658 (1970), and private communication. This is ≈ 20 events/μb exposure, and no conclusions on the $A_2$ splitting can be drawn.
12. U. Kruse, University of Illinois, private communication at this Conference. They have two exposures at 5 and 7 GeV/c incident $\pi^-$ corresponding to ≈ 15 events/μb. No conclusion can be drawn on the $A_2$ splitting.
13. For more information on this point see listings of Review of Particle Properties by the Particle Data Group, Rev. Mod. Phys. 42, 87 (1970).
14. M. L. Goldberger and K. M. Watson, Phys. Rev. 136B, 1472 (1964); K. E. Lassila and V. Ruuskanen, Phys. Rev. Letters 17, 49 (1966) and Phys. Rev. Letters 19, 762 (1967); and many others.
15. C. Rebbi and R. Slansky, Phys. Rev. 185, 1838 (1969), and Doubled Resonances in the Eigenchannel Representation, CalTech Report 68-227 (1970).
16. W. Kienzle, in Meson Spectroscopy, edited by C. Baltay and A. H. Rosenfeld (W. A. Benjamin, Inc., New York, 1968), p. 256.
17. This point has been widely discussed; see, for example, A. H. Rosenfeld et al., Rev. Mod. Phys. 40, 77 (1968); S.-Y. Fung et al., Phys. Rev. Letters 21, 47 (1968), and A. Barbaro-Galtieri and P. Söding, in Meson Spectroscopy,

edited by C. Baltay and A. H. Rosenfeld (W. A. Benjamin, Inc., New York, 1968), p. 137.

18. D. J. Crennell, U. Karshon, K. W. Lai, J. S. O'Neall, and J. M. Scarr, Phys. Rev. Letters 22, 1327 (1969).
19. See, for instance, H. Cramér, Mathematical Methods of Statistics (Princeton University, Princeton, N. J., 1946), p. 448, formula (30.6.2).
20. W. Beusch et al., Zurich-CERN Collaboration, Phys. Letters 25B, 357 (1967).
21. U. Kruse, Review of Spin and Parity Analysis in the $A_2$ Region, paper presented at this Conference.
22. Lawrence Radiation Laboratory Group A, same authors as Ref. 4, Study of f Mesons at 7 GeV/c, to be published.
23. A. S. Goldhaber, G. C. Fox, and C. Quigg, Phys. Letters 30B, 249, (1969).
24. R. C. Arnold and J. L. Uretsky, Phys. Rev. Letters, 23, 444, (1969).

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