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EXPERIMENTAL STUDY OF MULTIPARTICLE RESONANCE DECAYS

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Lawrence Radiation Laboratory
Berkeley, California
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EXPERIMENTAL STUDY OF MULTIPARTICLE RESONANCE DECAYS
Gerson Goldhaber
January 1965
I would also like to thank Professor Kursunoglu for arranging this conference and for inviting us to this beautiful spot. Needless to say, my talk will have quite a different "content" from the preceding two talks. In fact I will mention SU(6) only once; and this was it! I will try and give some connections to reality and will talk about some of the particles and resonances which are currently under study.

It would be very nice if in keeping with the development in symmetry schemes I could now present to you some dozen particles or resonances all nicely wrapped up with their isotopic spin, parity and other quantum numbers well established. Such feats have indeed been accomplished during the past five years. Many of the resonances which form the basis for the octet and decimet have been established together with their quantum numbers. However we must note that in all of the remarkable early discoveries, the $Y_1^*(1385)$, the $K^*(888)$, the $\rho$, the $\omega$ and so forth, one was dealing with resonances decaying into two or sometimes three of what were then called "elementary particles."

The new development in this field is that one has started to observe cases in which a resonance decays into a second resonance and a particle. These decays proceed through a two step process:
where \( a^{**} \) and \( a^* \) represent resonances while \( b, b', \) and \( b'' \) represent particles. In general \( a^{**} \) is produced in reactions \( c + d \rightarrow a^{**} + e \). We are thus dealing with at least four particles in the final states which complicate the experimental situation considerably. One simplifying feature which appears to occur frequently however is that the multiparticle resonance is produced peripherally, i.e., with small four momentum transfer to \( e \). We thus may represent the interaction by a Feynman diagram.

I will try and review for you today the status of some of these resonance states giving rise to multiparticle decay as well as some unsolved problems in particle physics.
The topics I want to discuss are:

1. $A_1(1090) \rightarrow \pi \rho$
   $A_2(1320) \rightarrow \pi \rho$
   $\rightarrow K \bar{K}$
   $\rightarrow \pi \eta$

2. $B(1220) \rightarrow \pi \omega$

3. $\chi(960) \text{ or } \eta'(960) \rightarrow \pi \pi \eta$

4. $H(975) \rightarrow \pi \rho \ (?)$

5. $K\pi(1175) \rightarrow K\pi \ (?)$
   $\rho(1220) \rightarrow K\rho \text{ or } K^*\pi$
   $K\pi(1270) \rightarrow K^*\pi \ (T = 3/2 )$
   $\rightarrow \rho K$

6. $\Xi^*(1820) \rightarrow \Xi^*(1530) + \pi$
   $\rightarrow \Lambda \bar{K}^-$
   $\rightarrow \Lambda \bar{K}^0$

7. $p \pi^+ \pi^+ (1560) \text{ enhancement}$

8. $K^*(1430) \rightarrow K\pi$

9. $K(725) \rightarrow K\pi$

10. $K^+K^+(1275) \ T=1, \ S=2 \ (?)$

11. $K\bar{K}(1410) \rightarrow K^*K \text{ enhancement}$

12. The $\rho$ puzzle
1. The np Enhancement Leading to $A_1$ and $A_2$

A mass enhancement has been observed in the three pion system in the experiments of Bellini et al.\textsuperscript{1} and by Huson and Fretter\textsuperscript{2} with $\pi^-$ mesons at $\sim18$ GeV/c. This work was done in the E.P. heavy liquid chamber exposed at CERN. The observed mass peak ranged from 1.0–1.4 BeV and was attributed to "diffraction dissociation" by the authors. More recently we have carried out a study\textsuperscript{3,4} of the $\pi^+p$ interaction in the BNL 20-inch hydrogen chamber at 3.65 BeV/c. We observed a definite mass peak in the $np$ system between 1.0–1.4 BeV with indication of structure. This was followed by results of Chung et al.\textsuperscript{5} and Aderholz et al.\textsuperscript{6} who both demonstrated the existence of two peaks in the $np$ mass region 1.0–1.4 BeV now called the $A_1$ and $A_2$ mesons. Fig. 1–1 shows the various experimental distributions done either by $\pi^-p$ or $\pi^+p$ experiments in the region from 3.2 to 4.0 BeV/c. Fig. 1–2 shows the summary of the $\pi^-p$ and $\pi^+p$ data showing remarkable agreement between the two, and finally the complete summary of the data available to me to date, indicating the very marked mass peaks. Fig. 1–3 shows $A_1$ and $A_2$ production in the $\pi^-p$ reaction at 8 BeV/c,\textsuperscript{7} while Fig. 1–4 shows evidence for it in $\bar{p}p$ annihilation at rest.\textsuperscript{8} Fig. 1–5 shows the latest results\textsuperscript{9} obtained with the heavy liquid chamber, with $\pi^-$ mesons at 16 GeV/c. These data show a much sharper peak in the general mass region now attributed to the $A_1$ meson. The indications from this work are that the large width observed in the earlier work\textsuperscript{1,2} was probably due to instrumental resolution problems.

The question is now what quantum numbers to assign to these mass peaks if they are indeed resonances? In the work of Chung et al. the additional decay mode $A_2 \to K\bar{K}$ was discovered.

\begin{align}
A_2^- &\to K^- + K^0 \\
A_2^0 &\to K^0 + K^0
\end{align}  

(1)
Fig. 1–6 shows the latest data on this reaction given by Miller at the Dubna Conference. Furthermore the decay mode \( A_2^+ \rightarrow \eta^0 + \pi^+ \) has been observed. Evidence for this was presented by Aderholz et al. (Fig. 1–7) and more recently by Trilling et al. (Fig. 1–8). Combining the results for the \( \pi \rho \), \( K\bar{K} \) and \( \pi\eta \) production the latter paper quotes the branching ratios given in Table I.

<table>
<thead>
<tr>
<th>Table I. Branching Ratio for ( A_2^+ ) Decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_2^+ \rightarrow \rho^0 \pi^+ )</td>
</tr>
<tr>
<td>( \rightarrow \rho^+ \pi^0 )</td>
</tr>
<tr>
<td>( \rightarrow K^+ K^0 )</td>
</tr>
<tr>
<td>( \rightarrow \eta^0 \pi^+ )</td>
</tr>
</tbody>
</table>

The \( \rho^+ \pi^0 \) mode is difficult to observe experimentally due to the presence of two neutral mesons. A number of experimenters find data consistent with it, but as yet there are no conclusive measurements of the branching ratios. There is no evidence at present for the direct reaction \( A_2^+ \rightarrow 3\pi \).

(a) The Quantum Numbers of the \( A_2 \)

If we are indeed observing a single particle, the \( A_2 \), decaying into the three modes \( \pi \rho \), \( \pi \eta \), and \( K\bar{K} \) the spin and parity of the \( A_2 \) are determined as was first noted by Chung et al. Namely the lowest allowed quantum number is \( 2^+ \). This is illustrated in Table II. The evidence for this assignment is based on the occurrence of mass peaks in the three systems at the same central mass value. Furthermore, we must note that the assignment that a single particle, the \( A_2 \), decays into those three modes violates the Bronzan-Low A quantum number. It would thus be very nice to obtain an indepen-
Table II

Allowed Spin and Parity Values
For Various A Decay Modes

For T=1, G=odd

<table>
<thead>
<tr>
<th>$J^P(\pi\rho)$</th>
<th>$J^P(\pi\eta)$</th>
<th>$J^P(\eta\eta)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^-$</td>
<td>$0^+$</td>
<td>$0^+$</td>
</tr>
<tr>
<td>$1^-$</td>
<td>$1^-$</td>
<td></td>
</tr>
<tr>
<td>$1^+$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$2^-$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$2^+$</td>
<td>$2^+$</td>
<td>$2^+$</td>
</tr>
</tbody>
</table>

Possible Values for $A_1$ from Absence of $\pi\eta$ and $\eta\eta$ Modes

Assigned to $A_2$ from Decay Mode Comparisons
Table III

Spin Assignment for the $A_2$ from Angular Distribution (or Dalitz plot Density) for the $\pi\rho$ Decay Mode

<table>
<thead>
<tr>
<th>Chung et al.</th>
<th>Lander et al.</th>
<th>Deutschmann et al.</th>
<th>Cason and Good</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3.2$ BeV/c</td>
<td>$3.5$ BeV/c</td>
<td>$8$ GeV/c</td>
<td>$7$ BeV/c</td>
<td></td>
</tr>
<tr>
<td>$\pi^-\rho^- \rightarrow$</td>
<td>$\pi^+\rho^-$</td>
<td>$\pi^+\rho^-$</td>
<td>$\pi^-\rho^-$</td>
<td></td>
</tr>
<tr>
<td>$0^-$</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$1^-$</td>
<td></td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
<td></td>
</tr>
<tr>
<td>$1^+ J=0$</td>
<td>$1^+ J=2$</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
<td></td>
</tr>
<tr>
<td>$2^-$</td>
<td></td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
<td></td>
</tr>
<tr>
<td>$2^+$</td>
<td>Consistent</td>
<td>$\checkmark$</td>
<td></td>
<td>$(\checkmark)$</td>
</tr>
</tbody>
</table>

$X$ = Inconsistent with quantum number

$\checkmark$ = Consistent with quantum number
dent measurement of the $A_2$ spin and parity assignment. Such attempts have been made by various experimenters by studying the decay distribution in the $np$ system following the method of Zemach and also Fraser, Fulco and Halpern. Some of these measurements are illustrated in Fig. 1-9 to 1-12. The results of such measurements are given in Table III. So far none of the experiments are yielding unique results, and some of them even disagree with the assignment $2^{+}$. I believe that the cause for this disagreement is probably due to the fact that background interference plays an important role here, and I will discuss it in connection with the $A_1$.

(b) The Quantum Numbers of the $A_1$

From the data studied so far the $A_1$ meson does not appear to decay into either the $\eta\pi$ or the $K\bar{K}$ modes. (Note added in proof. Some evidence for $A_1 \rightarrow \pi\eta$ was given by Aderholz et al (Fig. 1-7). This matter has again been brought up in a preprint I just received from the Saclay-Orsay-Bari-Bologna Collaboration. The evidence for the presence of this decay mode still looks inconclusive however). This would leave the $J^P$ assignments $0^-, 1^+$, and $2^-$, as indicated in Table I, as the possible quantum numbers for the $A_1$. The quantum numbers derived from the study of the $np$ system are given in Table IV. Taken at face value these results indicate $1^+$ or $2^-$ as possible $J^P$ assignments. In my judgment, however, the difficulty with this method, at least in the 3-4 BeV region lies in the fact that we are faced with a non-negligible competing process, namely background from the channel $np \rightarrow \rho^0 + N^*$. We have carried out some calculations to study the effect of this channel on all the phenomena occurring in the $\pi^+ p$ reaction. To this end we have written down the amplitudes corresponding to the Feynman diagram and have then carried out the evaluation of the integrals over phase space for the symmetrized system by a Monte Carlo method. While it is true that in all studies of the $A$ meson the $N^*$ band
TABLE IV

Spin Assignment for the \( A_1 \) from Angular Distributions
(or Dalitz Plot Density) for the \( np \) Decay Mode

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi^-p )</td>
<td>3.2 BeV/c</td>
<td>3.5 BeV/c</td>
<td>( \pi^- ) nuclei</td>
<td>( \pi^-p )</td>
<td>( pp ) at rest</td>
</tr>
<tr>
<td>( \pi^-p )</td>
<td>16 GeV/c</td>
<td>7 BeV/c</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0^-</td>
<td>(( \checkmark ))</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
</tr>
<tr>
<td>1^-</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
</tr>
<tr>
<td>1^+</td>
<td>( \ell = 0 )</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
</tr>
<tr>
<td>2^-</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
</tr>
<tr>
<td>2^+</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
</tr>
</tbody>
</table>

* This assignment was based on the peaking at low \( \pi \pi \) masses. At the Dubna Conference, the authors (Hess et al.) pointed out that this effect is probably due to the tail of the \( N^* \) band and retracted the assignment.
has been excluded one cannot escape the fact that a considerable $N^*$ amplitude due to the tail of the Breit–Wigner distribution, is still present throughout the region studied here. We have computed the matrix element corresponding to $\pi^+ + p \rightarrow \rho^0 + N^{**+}$ assuming one pion exchange. If we label the particles $\pi^+ \pi^- p$ as 1, 2, 3 and 4 then Bose symmetrization requires that we take the symmetrized matrix element

$$\left| M \right|^2 = \left| M(\rho_{13}, N_{24}^*) + M(\rho_{23}, N_{14}^*) \right|^2 \quad (1)$$

Here we have taken the approximation for $M(\rho_{13}, N_{24}^*)$ given by:

$$\left| M(\rho_{13}, N_{24}^*) \right|^2 \simeq \left( \cos^2 \alpha_{13} \right) \cdot \left( 1 + 3 \cos^2 \alpha_{24} \right)$$

where $\Gamma_\rho, \Gamma_N^*, \rho, M_\rho$ and $M_N^*$ are the full widths at half maximum and central mass values for S-wave Breit Wigner amplitudes for $\rho$ and $N^*$ formation respectively, $M_{ij}$ are the invariant masses for particles $i$ and $j$, $\Delta_{0,ij}^2, \alpha_{ij}$ is the four momentum transfer from the $0,ij$ vertex ($0$ refers to the incident particle), $\alpha_{ij}$ is the scattering angle in the center of mass of particles $i$ and $j$ with respect to the incident direction.

We find that on the above model we obtain a broad enhancement in the $3\pi$ mass distribution in the region from 1–1.3 BeV. The $A_2$ meson appears to be riding on this distribution as well as the $A_2^+$ meson to the extent that it sticks out above it. (See curve in Fig. 1–3). A further consequence of this model is a very marked enhancement at low $\pi^+ \pi^-$ masses which I believe is probably the cause...
of the peaking in the density distribution of the \( \rho \) band associated with the \( A_1 \) mesons. (See Fig. 1-13) This enhancement in the \( \rho \) band for \( M(\pi\pi) \approx 390 \text{ MeV} \) is particularly noticeable if we look at a \( \pi\pi \) vs. \( \pi\pi \) scatter plot without any restrictions on the \( 3\pi \) mass. This is shown in Fig. 1-14 and Fig. 1-15 for our data at 3.65 BeV/c for events inside and outside the \( N^{*++} \) band respectively. Paraphrasedly it is also clear from Fig. 1-14 that the \( \pi\pi \) enhancement observed in our experiment at \( M(\pi\pi) \approx 390 \) is a kinematic reflection associated with \( \rho \) and \( N^* \) formation rather than a distinct resonance.

One point to note here is that the density distribution in the \( \rho \) band for the \( A_1 \) meson is distinctly different for the \( \pi^+p \) data in the 3-4 BeV/c region (Figs. 1-9 to 1-11) and the \( \pi^- \) nuclei data at 16 BeV/c. Namely, the density of points in the region of the crossing \( \rho \) bands, i.e., the double \( \rho \) region is considerably higher in the former case than in the latter. This may indicate either (a) that the background from the \( \rho N^* \) process dominates the 3-4 BeV/c data or (b) that the phenomena observed in the hydrogen experiment at 3-4 BeV/c and the heavy liquid experiment at 16 BeV/c, respectively, correspond to different physical processes. A third possibility which cannot be ruled out at present is that the \( \rho \) density distribution at 16 BeV/c is the same as at the lower energy and that the observed deviation constitutes a statistical fluctuation.

Finally the question has been raised whether the \( A_1 \) is to be regarded as a bonafide resonance\(^3,4\) or due to some other mechanism. The Peierl's mechanism has frequently been suggested although the consensus of theoretical opinion appears to be at present that this mechanism cannot produce such a mass peak. From the experimental point of view the decay mode, \( A_1^+ \rightarrow \rho^+\pi^0 \) (which is expected to occur from charge independence but cannot occur on the Peierl's mechanism) has not been established. As I mentioned above, however, this mode involving \( 2\pi^0 \) mesons is fraught with experimental difficulties.
FIG 1-1
\[ \pi^- + p \rightarrow \rho^0 + \pi^- + p \]

GOLDHABER ET AL.
3.7 BeV/c

CHUNG ET AL.
3.2 BeV/c

COMBINED DATA
\[ \pi^+ + p \rightarrow \rho^0 + \pi^+ + p \]

\[ \pi^+ + p \rightarrow \rho^0 + \pi^+ + p \]

M\( (\pi^0) \) (MeV)

M\( (\pi^0) \) (MeV)

FIG 1-2
$\pi^+_p p \pi^+ \pi^+ \pi^-$ AT 8 GeV/c

N*++ EXCLUDED

AACHEN-BERLIN-CERN COLLABORATION

205 events
BETTINI ET AL. \( \bar{p} p \) AT REST

\[ M (p^0 \pi^\pm) \]
1458 comb.

Number of events

\[ M (p^0 \pi^\pm) \]

FIG 1-4
16 GeV/c $\pi^-$ on Nuclei

ECOLE POLYTECHNIQUE, CERN, MILANO, SACLAY, U.C. BERKELEY

$\pi^+\pi^-\pi^-$ Effective Mass

- All events (989)
- Low $q$ events
- Low $q$ events with $\phi$

Number of Events

$M_{3\pi}$ GeV

Fig 1-5
Fig 1-6
(Note added in Proof: Barmin et al. of Moscow presented data at the Dubna Conference showing structure in the $K^0_iK^0_i$ mass distribution. This work was done with $\pi^-$ mesons at 2.8 GeV/c in a bubble chamber filled with a propane-xenon mixture. They find a peak at $M(K^0_iK^0_i) \approx 1280$ MeV. They ascribe this peak either to the $A_2$ or the $f^0$. If the data represents $f^0$ decay they quote a ratio for $(f^0 \rightarrow K^0_iK^0_i)/(f^0 \rightarrow \pi^+\pi^-) \pm 2.3 \pm 1.0\%$. V. V. Barmin, A.G. Dolgolenko, I.A. Yerofeev, Yu.S. Krestnikov, A.G. Meshkovsky, G.D. Tikhomirov, Yu.V. Trebukhovsky, V.A. Shebanov. Preprint N. 284, Moscow 1964.)
(a) Missing mass distribution for reaction $n^+p \rightarrow p\pi^+ + \text{neutrals}$, (b) Effective mass distribution of $n^+$ combined with $\eta$ candidate. Solid histogram: for both channels $n^+p \rightarrow p\pi^+ + \text{neutrals}$ and $n^+p \rightarrow p\pi^+\pi^-\pi^0$; shaded histogram: only from $n^+p \rightarrow p\pi^+\pi^-\pi^0$. $N^+$ region removed and $\delta^2 < 0.6$ GeV$^2$. (c) Effective mass distribution of $n^+$ combined with missing neutrals for control regions on either side of the $\eta$ region of the reaction $n^+p \rightarrow p\pi^+ + \text{neutrals}$; $N^+$ region removed and $\delta^2 < 0.6$ GeV$^2$.
TRILLING et al. 3.65 GeV/c

\[ \pi^+ + p \rightarrow \pi^+ + p + \eta \]

- All events
- \( \eta \rightarrow \pi^+ \pi^- \pi^0 \) only

Events vs. \( M_{\pi\eta} \) (MeV)

Fig 1-8
\[ \pi^- p \text{ CHUNG ET AL.} \]

3.2 BeV/c

\[ M_{\pi^+\pi^-}^2 \text{ (BeV)}^2 \]

Number of events

\[ M_{\pi^+\pi^-}^2 \text{ (BeV)}^2 \]

\text{Fig 1-9}
\[ \pi^+ p \] LANDING ET AL.

3.5 BeV/c

**Fig 1-10**
AACHEN-BERLIN-CERN COLLABORATION

\[ \pi^+ p \rightarrow p \pi^+ \pi^+ \pi^- \] at 8 GeV/c

1.125 \leq (\pi^+ \pi^+ \pi^-)_{\text{mass}} \leq 1.4 \text{ GeV}

Fig 1-11
16 GeV/c $\pi^-$ on Nuclei

ECOLE POLYTECHNIQUE, CERN, MILANO, SACLAY, U.C. BERKELEY

$q < 150$ Mev/c

a)

M$_{\pi\pi}^2$ vs M$_{\pi\pi}$

M$_{\pi\pi}^2$ = 1160 Mev

M$_{\pi\pi}^2$ = 1000 Mev

b)

M$_{\pi\pi}^2$ vs M$_{\pi\pi}$

Fig 1-12
Fig 1-14
2. The $\pi\omega$ Enhancement or "B" Meson

A marked enhancement in the $\pi\omega$ system centered at 1220 MeV was noted independently by three groups studying the $\pi^+$ and $\pi^-p$ reactions respectively in the 3.2-3.65 BeV/c region. These are Abolins et al. $\pi^+p$ at 3.4 to 3.5 BeV/c; Miller et al. $\pi^-p$ at 3.2 BeV/c and in our own work, $\pi^+p$ at 3.65 BeV/c. The effect was called the "B" meson by Abolins et al. All information available to me on the present status of this $\pi\omega$ enhancement is shown in Fig. 2-1.

Fig. 2-2 shows the combined data from all the above experiments and as can be noted shows a very clearcut peak at $E_B = 1220$ MeV and with a width that is somewhat larger than quoted for the individual experiments namely $\Gamma_B = 130$ MeV. If this peak is a bonafide resonance it corresponds to $T=1$ and $G$ even.

Hess et al. have also looked for the B meson in the $\pi^-p$ reaction at 4.2 BeV/c. There the evidence for B production is much weaker but it is noteworthy that $\omega$ production itself is considerably smaller too. This data has not been included in Fig. 2-2.

The angular momentum and parity of the B meson have been investigated by examining angular distribution in the $\omega$ rest frame and by a method suggested by Halpern. The data so far are not conclusive. A suggestion by Fraser et al. that the B meson is another decay mode of the $f^0$, both carrying the quantum numbers $T^GJ^P = 1^-+ -$ led to a careful investigation of the $f^0$ by experimenters all over the world who demonstrated rather clearly that a charged mode of the $F^0$ does not exist.

There are two further comments I would like to make which concern the background problems in the study of the B meson: The first one is a purely experimental point, that is that one can obtain kinematical peaks if in the reaction $\pi^+p \rightarrow \pi^+\pi^0\pi^+\pi^-$, one
constrains three of the \( \pi \) mesons \( \pi^+_a \pi^- \pi^0 \) to lie within a certain mass region. This is illustrated for the mass region 510–710 MeV, i.e., below the \( \omega \) meson (see Fig. 2–3). If one now looks at the four pion spectrum one obtains a very marked peak at 1010 MeV, of width 80 MeV. (see Fig. 2–4) The first inclination is to say, "Well, there's another one." It is relatively easy to convince oneself however that this peak is due to the over-constraints which have been imposed on this system, namely the \( \pi^+_a \pi^- \pi^0 \) mass value now gets combined with the \( \pi^+_b \) which belongs to an \( \omega \). In fact if we now remove the \( \omega \) band we obtain the shaded distribution in which the peak has been removed to a large extent. Having learned the lesson from this example we now ask what happens in any of the above experiments when we confine ourselves to the \( \omega \) band. By these means we choose the majority of the real \( \omega \) meson but of necessity the data also includes from 25–40% of background events. These background \( \omega \)'s, however, are now also "kinematically constrained" and if we consider that for some cases two \( \pi^+_a \pi^- \pi^0 \) of the three pions are part of a true \( \omega \) than we have imposed a double constraint on the four pion system. This will again lead to a "kinematical peak". It happens that this kinematical peak falls in the general mass region ascribed to the B meson. The majority of the constrained events corresponds to "double \( \omega \) events", i.e., both \( \pi^+_a \pi^- \pi^0 \) masses lie in the \( \omega \) band. As such they are counted only one in the four pion mass distribution. The events which are introduced artificially are the ones corresponding to a "background \( \omega \)" which is associated with a try \( \omega \) from the "resonance tail" (see Fig. 2–5).

The second comment on the B background problem comes from the modification of phase space arising from the presence of identical bosons. If we carry out a calculation where we consider \( \omega N \) production and again symmetrize the Feynman diagram corresponding to this reaction, we obtain a considerable modification of the phase space for the four particle mass when \( \omega \) events are selected. Indeed this modified phase space is enhanced in the general vicinity of the B meson. At this time I just
wish to point out these two complications and that as far as spin evaluations for the B meson are concerned, one has to take these two sources of background into account.

From the experimental point of view this can be appreciated by considering a $M^2(\pi^+\pi^-\pi^0)$ versus $M^2(\pi^+\pi^-\pi^0)$ scatter plot. The region contributing to the B meson contains the overlap of the two $\omega$ bands. This is illustrated in Fig. 2-6 and in enlarged form in Fig. 2-7.
ABOLINS ET AL.
$\pi^+p$ 3.43, 3.54 BeV/c

HESS ET AL.
$\pi^-p$ 3.2 BeV/c

GOLDHABER ET AL.
$\pi^+p$ 3.65 BeV/c

Fig 2-1
Fig 2-2

Author | p(BeV/c) | 
--- | --- | 
π⁺ₚ ABOLINS ET AL. | 3.43, 3.54 | 
π⁺ₚ A-B-B-H-L-M coll. | 4.0 | 
π⁺ₚ GOLDHABER ET AL. | 3.65 | 
π⁺ₚ HESS ET AL. | 3.2 |
Fig 2-3

(a) \( \pi^+ p \rightarrow \pi^+ K^- K^0 \pi^+ p \), 3.65 BeV/c

(b) Number of events per 20 MeV

(c) \( \pi^+ K^- K^0 \) and \( \pi^+ K^- K^0 \) 2x645 triplets
   Type 3
   225 above phase space

(d) \( \pi^+ K^- K^0 \) 1352 triplets
   Types 1 and 2
   18 above phase space

(e) Number of events per 40 MeV

(f) Number of events per 40 MeV

(g) \( \pi^+ K^- K^0 \) 1144 triplets
   Type 1
   "N reflection"

(h) \( \pi^+ K^- K^0 \) and \( \pi^+ K^- K^0 \) 2x1997 triplets
   All types
   630 triplets above phase space
Example of "kinematical peak"

Produced for

$510 \leq M(\pi^+\pi^-\pi^0) \leq 710$ MeV

1010 MeV

\boxed{\omega \text{ band excluded}}

\[ \pi^+ + p \rightarrow \pi^+\pi^-\pi^0\pi^+ + p \quad 3.65 \text{ BeV/c} \]
Fig 2-5

$M(\pi^+\pi^-\pi^0)$

"Resonance Band"

"Resonance Tail"

Background Events
$\pi^+ p \rightarrow \pi^+ \pi^- \pi^0 \pi^+ p \quad 3.65 \text{GeV}/c$

FILTER = NONE \hspace{1cm} 2 \times 1997 \hspace{0.5cm} TRIPLETS

$M^2(\pi^+ \pi^- \pi^0) \hspace{1cm} (\text{BeV})^2$

$M^2(\pi^+ \pi^- \pi^0) \hspace{1cm} (\text{BeV})^2$

Fig 2-6
$M^2 \left( \pi^+ \pi^- \pi^0 \right) (\text{BeV})^2$
3. **The $X^0(960) \rightarrow \pi\pi\eta$ Resonance or $\eta'(960)$**

A very beautiful example of a resonance decaying into another resonance and two additional particles has been observed in two recent experiments. This is the $X^0(960) \rightarrow \pi\pi\eta$ (see Fig. 3-1). I will keep my remarks brief as a very extensive description of this resonance has appeared in a series of five notes to the Physical Review Letters. The description of the resonance is given by the Syracuse Brookhaven groups, Goldberg et al.\textsuperscript{1,4}, who studied the $K^-p$ reaction at 2.3 BeV/c and by a Berkeley group, Kalbfleisch et al.\textsuperscript{2,3} who studied the same reaction at 2.45-2.7 BeV/c.

The spin analysis is described in three subsequent notes by the above groups and also by the Los Angeles group, Dauber et al.\textsuperscript{5}, who studied the $K^-p$ reaction at 1.8-1.95 BeV/c. In all experiments the effect is observed in the reaction $K^- + p \rightarrow \Lambda + X^0$ with the identified decay modes of the $X^0$ occurring as

\[
X^0 \rightarrow \pi^+ + \pi^- + \eta^0 \\
\quad \downarrow \pi^+ \pi^- \pi^0 \\
\quad \downarrow \text{neutrals} \\
\rightarrow \pi^0 + \pi^0 + \eta^0 \\
\quad \downarrow \pi^+ \pi^- \pi^0 \\
\quad \downarrow \text{neutrals} \\
\rightarrow \pi^+ + \pi^- + \gamma
\]

Needless to say the unravelling of all the various decay modes posed formidable experimental difficulties. These are described in detail in the literature I cited.
The mass and width quoted for the $X_0$ are

<table>
<thead>
<tr>
<th>M MeV</th>
<th>$\Gamma$ MeV</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>960 ± 5</td>
<td>&lt; 20</td>
<td>Goldberg et al.</td>
</tr>
<tr>
<td>959 ± 2</td>
<td>&lt; 12</td>
<td>Kalbfleisch et al.</td>
</tr>
<tr>
<td>957</td>
<td>&lt; 4</td>
<td>Dauber et al.</td>
</tr>
</tbody>
</table>

All authors agree that the width is consistent with being too small to measure by the usual bubble chamber techniques. The quantum numbers and other properties can be described in the following steps:

(a) From the production process $T(X^0) = 0$ or 1
(b) No evidence for $X^0 \rightarrow 5\pi$ directly
(c) $X^0 \rightarrow 3\pi$, this suggests that $G$ is conserved in the decay yielding $G = +1$
(d) If $X^0 \rightarrow \pi^0 + \pi^0 + \eta^0$ then $T = 0$. Strong arguments favoring this decay mode were given by Kalbfleisch et al. on the basis of the large average number of $\gamma$'s observed with the $X^0 \rightarrow$ neutrals mode. They thus conclude $T = 0$.
(e) Goldberg et al. conclude on the basis of decay angular distributions and density distribution of the Dalitz plot that $T, J^P$ values of $0,0^-$ and $1, 1^+$ are consistent with their data. See Fig. 3-2. This ambiguity is not resolved by a study of the experimental ratio of the various decay modes. (see Fig. 3-2, Table I).
(f) Dauber et al. conclude on the basis of the Dalitz plot density distribution that $T, J^P$ values of $0,0^-$ (best fit) and $0,2^-$ as well as $0,1^+$ (if the $\Sigma$ is invoked) are possible. This is illustrated in Fig. 3-3 where the table gives the deviation of the experimental likelihood from the theoretical value in units of the variance. They further find that the distribution of the $X_0$ decay normal with respect to the incident direction corresponds to $J^P = 0^-$ however $1^+$ and $2^-$ cannot be ruled out. They also present some evidence for $X^0 \rightarrow \pi\pi\gamma$. 
Kalbfleisch et al. present evidence for the decay mode $X_0 \rightarrow \pi^+ \pi^- \gamma$

$\left(22 \pm 4\%ight)$ and conclude from the distribution of the $\pi^+ \gamma$ angle together with the $\pi\pi\gamma$ Dalitz plot and $T=0$ from (d) that $TJ^P = 0,0^-$. Here they must invoke a $\sigma$ to explain the $\pi^+ \pi^-$ mass distribution. (see Fig. 3-4).

On all the above evidence the $X^0$ appears to be a "heavy $\eta^0$" or $\eta'(960)$.

The $X^0$ may thus be the pseudoscalar meson belonging to the SU(3) singlet representation or the "ninth meson" discussed by Schwinger recently.
Fig. 3. Two-dimensional plot of $M^2(\pi^+\pi^-\text{neutrals})$ vs $\cos\theta$ for the 415 events in channel (3), $K^- p \rightarrow \Lambda + \pi^+ + \pi^- + \text{(neutrals with mass } > m_{\pi})$. See text for description of included curves and regions A, B, and C.

**K^- p 2.45 - 2.7 BeV/c**

**KALBFLEISCH** et al.

**K^- p 1.8 - 1.95 BeV/c**

**DAUBER** et al.

---

**FIG. 1.** (a) Distribution of the effective mass squared of $\pi^+\pi^-\eta\pi^-$ in the reaction $K^- p \rightarrow \Lambda + \pi^+ + \pi^- + \text{neutrals}$. The shaded area represents events in which the square of the momentum transfer from the proton to the lambda, $\Delta p^2$, is less than 0.5 BeV$^2$. (b) Distribution of the effective mass squared of all four $\pi^+\pi^-\eta\pi^-$ combinations in the 35 $\Lambda^0 + \pi^+ + \pi^- + \text{neutrals}$ events in (a) where 0.86 BeV$^2 < M^2(5\pi) < 0.98$ BeV$^2$. The data are at incident momenta of 2.45, 2.63, and 2.70 BeV/c.
FIG. 3. (a) and (b) Angular and momentum dependence of the square of the (simplest) \( X^0 \) decay matrix elements compared with theoretical predictions (see Table I). Background has been subtracted from experimental points.

### Table I. \( X^0 \) decay modes. \( X^0 \) decay final state.

<table>
<thead>
<tr>
<th>( I, J^P )</th>
<th>( \pi^+ \pi^- \pi^+ \pi^- ) (B)</th>
<th>( \pi^+ \pi^- ) neutrals (C)</th>
<th>All neutrals (A)</th>
<th>( \pi^+ \pi^- \gamma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 0^+, 0^- )</td>
<td>( \eta^+ \pi^- )</td>
<td>( \eta^+ \pi^- )</td>
<td>( \eta^+ \pi^- )</td>
<td>( \eta^+ \pi^- )</td>
</tr>
<tr>
<td>( 1^+, 1^- )</td>
<td>( \eta^+ \pi^- )</td>
<td>( \eta^+ \pi^- )</td>
<td>( \eta^+ \pi^- )</td>
<td>( \eta^+ \pi^- )</td>
</tr>
</tbody>
</table>

### Table II. \( X^0 \) decay matrix elements.

| \( J^P \) | \( I \) | \( \eta^0 \) | \( \eta^+ \) | \( \eta^- \) |
|----------|--------|--------|--------|
| \( 0^+ \) | 0 | 0.166 | 0.566 | 0.234 |
| \( 0^- \) | 1 | 0.166 | 0.566 | 0.234 |
| \( 1^+ \) | 0 | 1.111 | 0.111 | 0.111 |
| \( 1^- \) | 1 | 0.111 | 1.111 | 0.111 |
| \( 2^+ \) | 0 | 2.123 | 0.123 | 0.123 |
| \( 2^- \) | 1 | 0.212 | 2.123 | 0.212 |

### Footnotes

- (A) All neutrals
- (B) \( \pi^+ \pi^- \pi^+ \pi^- \)
- (C) \( \pi^+ \pi^- \) neutrals
- \( \eta^0 \) decay
- \( \eta^+ \) decay
- \( \eta^- \) decay

---

Goldberg et al.
Table I. Dalitz-plot densities for $T=0, 1$, and various $J^P$ assignments, and results of maximum-likelihood fitting procedure.

<table>
<thead>
<tr>
<th>$T$</th>
<th>$J^P$</th>
<th>$D_{J',P,T}$</th>
<th>$\Delta/\nu$ This exp. plus data</th>
<th>$\Delta/\nu$ with $\sigma^a$ This exp. plus data</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$0^-$</td>
<td>$\rho^2 q^2 \cos^2 \theta$</td>
<td>-13.7</td>
<td>-16.7</td>
</tr>
<tr>
<td></td>
<td>$1^+$</td>
<td>$\rho^2 q^2$</td>
<td>-4.3</td>
<td>-4.3</td>
</tr>
<tr>
<td></td>
<td>$1^-$</td>
<td>$\rho^2 q^2 \sin^2 \theta$</td>
<td>-4.0</td>
<td>-10.1</td>
</tr>
<tr>
<td></td>
<td>$2^+$</td>
<td>$\rho^2 q^2 \sin^2 \theta$</td>
<td>-6.6</td>
<td>-14.6</td>
</tr>
<tr>
<td></td>
<td>$2^-$</td>
<td>$\rho^2 q^2 (1 + \frac{1}{2} \cos 2 \theta)$</td>
<td>-1.2</td>
<td>-2.2</td>
</tr>
<tr>
<td>0</td>
<td>$0^-$</td>
<td>1</td>
<td>+1.1</td>
<td>+0.9</td>
</tr>
<tr>
<td></td>
<td>$1^+$</td>
<td>$\rho^2$</td>
<td>-4.3</td>
<td>-6.4</td>
</tr>
<tr>
<td></td>
<td>$1^-$</td>
<td>$\rho^2 q^4 \cos^2 \theta \sin^2 \theta$</td>
<td>-11.6</td>
<td>-16.7</td>
</tr>
<tr>
<td></td>
<td>$2^+$</td>
<td>$\rho^2 q^2 \sin^2 \theta$</td>
<td>-8.2</td>
<td>-12.4</td>
</tr>
<tr>
<td></td>
<td>$2^-$</td>
<td>$\langle</td>
<td>a</td>
<td>^2 p^2 +</td>
</tr>
</tbody>
</table>

$^a$Using $D' = D[(M_0 q^2 - M_0^2)^2 + (M_0 q^2)^2]^{-1}$ with $M_0 = 380$ MeV, $\Gamma_0 = 80$ MeV.

$^b$See reference 1.

$^c$Because of the availability of the fitting parameter $b/a$, the procedure is different in this case. The data fit well for $b/a \sim 3$.

FIG. 3. (a) Dalitz-Fabri plot for the decays $X^0 \rightarrow \pi^+ + \pi^- + \eta$ and $X^0 \rightarrow \pi^+ + \pi^- + \eta_c$ for events fitted to hypothesis "X": $K^- + \rho - A + X^0, X^0 \rightarrow 2\pi + \eta$. Charge symmetry permits folding about the AB line. (b) Histogram of the effective mass of the di-pion in $X^0 \rightarrow 2\pi + \eta$. The smooth curves represent phase space appropriate to a $0^-$ particle, $p^2 \phi$ for a $1^+$ particle. The dashed curves include the effect of the $\sigma$.

DAUBER et al.
FIG. 3. (a) Distribution of the effective mass squared of the $s^+s^-$ system in the 40 $s^+s^-\gamma$ events with 0.80 (BeV)$^2 \leq M^2(s^+s^-\gamma) \leq 0.94$ (BeV)$^2$ and in the two $s^+s^-\gamma$ ("visible" gamma) events. The estimated background contribution to these events is cross hatched. Shown are the curves for the predicted distributions corresponding to $(J^P=0^-, C=+1, \text{no } \rho)$ and $(J^P=0^-, C=+1, \text{with } \rho)$ matrix elements (see Table I).

The curves are normalized to the number of events, excluding background. (b) Distribution of the events (a) in the angle $\theta_{\pi+\gamma}$ between the $\pi^+$ and the $\gamma$, measured in the di-pion rest frame. The normalized curves of $\sin^2 \theta$ and $1 + \cos^2 \theta$ represent the two extreme cases for the matrix elements of Table I.

Table I. Simplest matrix elements for decay into the $s^+s^-\gamma$ system, via ED and MD transitions. Here we have

$p^+ = \bar{p}_{\pi+} - \bar{p}_{\pi-}$, $k_E = \hat{\alpha} \times \bar{p}_{\gamma}$, $k_M = (\hat{\alpha} \times \bar{p}_{\gamma}) \times \bar{p}_{\gamma}$, $q_E = p \times k_E$, and $q_M = p \times k_M; \hat{\alpha}$ is a unit pseudovector along the direction of the magnetic field of the photon, and $\theta$ is the angle between the $s^+$ and $\gamma$ in the di-pion rest frame.

<table>
<thead>
<tr>
<th>$C$</th>
<th>$J^P$</th>
<th>$l$</th>
<th>Mode</th>
<th>Matrix element</th>
<th>Angular dependence</th>
</tr>
</thead>
<tbody>
<tr>
<td>$+1$</td>
<td>$0^-$</td>
<td>1</td>
<td>MD</td>
<td>$\vec{p} \cdot \vec{k}_M$</td>
<td>$\sin^2 \theta$</td>
</tr>
<tr>
<td></td>
<td>$1^+$</td>
<td>1</td>
<td>ED</td>
<td>$q_E$</td>
<td>$1 + \cos^2 \theta$</td>
</tr>
<tr>
<td></td>
<td>$1^+$</td>
<td>1</td>
<td>MD</td>
<td>$q_M$</td>
<td>$1 + \cos^2 \theta$</td>
</tr>
<tr>
<td></td>
<td>$2^+$</td>
<td>1</td>
<td>ED</td>
<td>$\vec{p} \cdot (\vec{k}_E - i\vec{k}_M)$</td>
<td>$6 + \sin^2 \theta$</td>
</tr>
<tr>
<td></td>
<td>$2^-$</td>
<td>1</td>
<td>MD</td>
<td>$\vec{p} \cdot (\vec{k}_M + i\vec{k}_E)$</td>
<td>$6 + \sin^2 \theta$</td>
</tr>
<tr>
<td>$-1$</td>
<td>$0^-$</td>
<td>1</td>
<td>MD</td>
<td>(Forbidden via dipole mode)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>$1^+$</td>
<td>0</td>
<td>MD</td>
<td>$k_M$</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>$1^-$</td>
<td>0</td>
<td>ED</td>
<td>$k_E$</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>$2^+$</td>
<td>2</td>
<td>MD</td>
<td>$\vec{p} \cdot (\vec{k}_M + i\vec{k}_E)$</td>
<td>$1 + \cos^2 \theta$</td>
</tr>
<tr>
<td></td>
<td>$2^-$</td>
<td>2</td>
<td>ED</td>
<td>$\vec{p} \cdot (\vec{k}_E + i\vec{k}_M)$</td>
<td>$1 + \cos^2 \theta$</td>
</tr>
</tbody>
</table>
4. The $\pi^+\pi^-\pi^0$ Enhancement at 975 MeV or H Meson

In the $\pi^+p$ experiment at 4 BeV/c carried out by the Anglo-German collaboration a further $\pi\rho$ enhancement with $T=0$ was observed in the reaction $\pi^+ + p \rightarrow \pi^+\pi^-\pi^0p$. A suggested reaction is $\pi^+ + p \rightarrow \rho^+ + \pi^- + \pi^0 + p$ where then the $H$ decays into $\rho^+,\pi^-\pi^0 + \pi^+$ with $E_H = 975 \pm 15$ MeV and $\Gamma_H = 120$ MeV. We have looked at our data at 3.65 BeV/c and also observed a slight deviation from phase space in that same general vicinity. In Fig. 4-1 I show the data for the Anglo-German collaboration. In Fig. 4-2 I show our data and then the combined data for both experiments. As may be noted on adding the two sets of data while there still appears to be a shoulder present near 975 MeV the effect appears decreased if anything. The establishment of a definite resonance will thus require considerably more work.
Fig. 2. Effective mass distribution of $\pi^+\pi^+\pi^-\pi^-\pi^0$ for reaction $\pi^+p \rightarrow \pi^+\pi^+\pi^-\pi^-\pi^0$ when $\pi^+\pi^0$ is in $N^-$ region. a) when at least one of the combinations $\pi^+\pi^-$, $\pi^+\pi^0$, $\pi^-\pi^-$ is in the $\rho$ region (0.64 GeV < $M_{\pi\pi}$ < 0.86 GeV), b) without constraint on dipion masses.
\( \pi^+ + p \rightarrow N^{*++} + \pi^+ + \pi^- + \pi^0 \)

3.65 BeV/c

\( \rho^+, \rho^- \) or \( \rho^0 \) selected

\( \omega^0 \) removed

\( \Delta^2 \leq 50 \text{ m}^2 \)

A-B-B-H-L-M collaboration

4.0 BeV/c \( \pi^+ p \)

Goldhaber et al.

3.65 BeV/c \( \pi^+ p \)

**Fig 4-2**
5. The $K\pi$ Enhancements

Three distinct $K\pi$ mass enhancements have been reported in the literature.\(^1\)

(a) In the reaction

\[
\pi^- p \rightarrow \Lambda K\pi \\
\rightarrow \Sigma K\pi
\]

at 3 BeV/c Wangler et al. observed a $K\pi$ enhancement at 1175 MeV. (see Fig. 5-1) This peak was not observed by Hardy et al. who studied the same reaction at 2.86, 3.01 and 3.21 BeV/c. Hardy et al. did however observe a peak at ~1220 MeV which occurred exclusively in the 3.01 BeV/c data (see Fig. 5-2). (Note added in proof: D. H. Miller et al. from Purdue reported at the 1965 New York APS Meeting that they do observe a peak at 1175 MeV in the same reaction at 2.7 BeV/c. (see Fig. 5-3). These three experiments are thus inconsistent with each other and more work will be required to see whether the inconsistencies are statistical or systematic in nature.

(b) The CERN-College de France Paris Group have studied the reaction:

\[
\bar{p}p \text{ (at rest)} \rightarrow K\bar{K}\pi
\]

In particular in the channel $K_1^- K_1^+ \pi^-$ (see Fig. 5-4) they observed an enhancement at 1215 MeV

\[
C^0(1215) \rightarrow K\pi \\
\rightarrow K\rho \\
\rightarrow K^*\pi
\]

One peculiar feature is that so far this enhancement has only been seen in the neutral form. If they consider the charged combination e.g. $K_1^0 \pi^0 \pi^0$ they see a possible enhancement at ~1320 MeV. The same general phenomenon has also been
observed by the Columbia-Rutgers-Brookhaven⁶(see Fig. 5-5). While at first there were some discrepancies in the relative importance of the Kp versus K⁺π⁻ decay modes Armenteros¹ feels that these are now ironed out. It was hoped to determine the isotopic spin of the C⁰ from charge independence in the branching ratios. These results are inconclusive as yet as given in Table 5-I.

---

**TABLE 5-I. C⁰ Decay Branching Ratio from Charge Independence**

<table>
<thead>
<tr>
<th>Branching Ratio</th>
<th>T=1/2</th>
<th>T=3/2</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>K⁺O O⁻</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K⁺±π±⁺</td>
<td>1</td>
<td>4</td>
<td>~0.9</td>
</tr>
<tr>
<td>ρ⁺k⁺</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O⁻k⁺</td>
<td>2</td>
<td>0.5</td>
<td>~0.82</td>
</tr>
</tbody>
</table>

---
The CERN - E. P. Paris and I. C. London Group observed a peak in the $K\pi$ system with $T_Z = 3/2$ at 1270 MeV. This work was done in the reaction $pp \rightarrow K^0 K^+ \pi^+ \pi^- \pi^0$ at 3 BeV/c. They report

$$K\pi (1270) \rightarrow K\pi$$

$$\rightarrow K\rho$$

in the ratio 3:1 which is consistent with phase space for the decay of a mass 1270 object. Fig. 5-6 shows their results which indicate a distinct mass peak. (Note added in Proof: Yeh et al. of Yale and Brookhaven reported on a study of the same channel at 3.7 BeV/c at the 1965 New York APS Meeting. With comparable statistics they do not observe the 1270 peak. While resonance production is known to be energy sensitive Yeh et al point out that in particular in $pp$ annihilation the difference in incident momentum represents only a small percentage change in the available energy). Finally Butterworth et al. reported work carried out in our group on the reaction $K^+ + d \rightarrow K^+ \pi^+ \pi^- \pi^0$. Here again some structure is observed in the $K\pi$ mass distribution (see Fig. 5-7) It is not clear however at present how much of this structure is to be ascribed to reflection from other processes, i.e., $K^* + N^*$ production $\rho + K + p$ production, etc.
3.0 GeV/c π⁻p  WANGLER et al

K⁺π⁻π⁻
K⁺π⁺π⁻
K⁺π⁺π⁺
K⁺π⁻π⁺
K⁺π⁻π⁻

\[ T_z = \pm \frac{1}{2} \]

\[ \pi^+ p \rightarrow \Lambda K \pi \pi \]
\[ \rightarrow \Sigma K \pi \pi \]

164 EVENTS
2.86-3.21 GeV/\epsilon \pi^+p \text{ INTERACTIONS} - (Hardy et al.)

- Figure 5-2
$\pi^- p \rightarrow \Upsilon K \pi \pi$ 2.7 GeV/c

Miller et al. Purdue U.

242 Events

$\Upsilon^*$ Band Out

Fig 5-3
\( \vec{p} p \) \text{ at rest (CERN- Col. de France, Paris)}

\[ \vec{p} + p \rightarrow K^0 K^0 \pi^+ \pi^- \]

\( M^2(K^0 \pi^+ \pi^-) \)

Curves:
- Curve \( \alpha \): Phase space
- Curve \( \beta \): \((Kp)\) phase space in \( \vec{p} + p \rightarrow K^0 K^0 p \)
- Curve \( \gamma \): 40% phase space +60\% \( \vec{p} p \rightarrow K^0 p^0 \) with \( C^0 \rightarrow K^0 p^0 \)

\( M(C) = 1215 \text{ MeV} \)
\( \Gamma(C) = 60 \text{ MeV} \)

Fig 5-4
ALL KK ππ EVENTS
\( \bar{p} + p \rightarrow KK \pi \pi \)
2 x 2778 EVENTS
-- PHASE SPACE
--- 60% C \( \rightarrow K + \rho \)
--- 40% PHASE SPACE
--- 100% C \( \rightarrow K^* + \pi \)

**Fig 5-5**
$\bar{p}p$ AT REST (CERN - E.P. PARIS - I.C. LONDON)

$K^0_1 K^+\pi^0\pi^+\pi^-\pi^0$

**Fig 5-6**

- a) $K^{*+}\pi$ and $K\pi$
  - $T_2 = \frac{3}{2}$

- b) $K^{*+}\pi$
  - $|T_2| = \frac{3}{2}$
BUTTERWORTH et al., $K^+d \rightarrow K^+\pi^-\pi^+p(n)$
2.3 BeV/c

$K^+d \rightarrow K^+\pi^-\pi^+p(n)$
2.3 BeV/c

Fig 5-7
6. The $\Xi\pi\pi$ Enhancement or $\Xi^*(1820)$

Smith et al.\(^1\),\(^2\) have been studying reactions of the type

\[
\begin{align*}
K^- + p & \rightarrow \Xi K\pi & (1) \\
& \rightarrow \Xi K\pi & (2) \\
& \rightarrow \Lambda K\bar{K} & (3)
\end{align*}
\]

at a momentum of 2.45–2.7 BeV/c. In this work they have observed a small enhancement in the $\Xi\pi\pi$ channel at 1820 MeV. They have interpreted this as the formation of $\Xi^*(1820) \rightarrow \Xi(1530) + \pi$

\[\Xi \rightarrow \Xi + \pi\]

More recently they have also observed an enhancement in the $K\Lambda$ mass in channel 3 (see Fig. 6–1). This decay mode was also observed by the Amsterdam, E.P. Paris and Saclay Group (see Fig. 6–2). In the neutral mode one cannot distinguish between $K^0\Lambda$ and $\bar{K}^0\Lambda$ which are $S=0$ and $S=2$ states respectively. The assignment $S=-2$ is obtained from the corresponding mass peak in the $K^-\Lambda^0$ mode as well as in reactions 1 and 2 giving $\Xi\pi\pi$ and $\Xi\pi$ enhancements at 1820 MeV.
FIG. 1. Dalitz plot and mass projections for the reactions \( \Lambda^0 K^- K^0 \) (341 events) and \( \Lambda^0 K^+ K^- \) (357 events). On the Dalitz plot, one \( \Delta R^3 \) (or \( \Delta R^2 \)) point per event is plotted, whereas on the projection, both \( \Delta R^3 \) and \( \Delta R^2 \) values are plotted. Events with a \( \varphi \) \( [1000 \leq M(K\pi) \leq 1040 \text{ MeV}] \) are not included in the projections. The envelopes on the Dalitz plot are for incident momenta of 2.45 and 2.70 BeV/c.

FIG. 2. (a) \( \Xi^+ (1530) \pi \) and \( \Xi \pi \pi \) mass projection for the reactions \( \Xi^+ K^0 \pi^- \), \( \Xi^- K^+ \pi^- \), and \( \Xi^- K^0 \pi^0 \). Shaded events also include a \( K^* \) \( [860 \leq M(K\pi) \leq 920 \text{ MeV}] \) for all \( l_x = \pm 1 \) \( K\pi \) combinations. The curve is our best estimate of the background for the non-\( K^* \) events. (b) and (c) \( \Xi \pi \) mass projections for the reactions \( \Xi^- K^+ \pi^- \) and \( \Xi^- K^0 \pi^0 \). Shaded events also include a \( K^* \) \( [850 \leq M(K\pi) \leq 950 \text{ MeV}] \). The curves are our best estimates of the background for all data.

SMITH et al.

\( K^- p 2.45-2.70 \text{ BeV/c} \)

Fig 6-1
AMSTERDAM
E.P. PARIS SACLAY

$K^- p \rightarrow \Lambda^0 K \bar{K}$

3 GeV/c

$M(\Lambda^0 K^-)$

$M(\Lambda^0 K^0 - \Lambda^0 \bar{K}^0)$

$\Lambda^0 K^0 + \Lambda \bar{K}^0 + \Lambda \bar{K}^-$ eff. mass

($\psi^0$ removed)

Fig 6-2
7. The $p\pi^+\pi^+$ Enhancement at 1560 MeV

In our work on the $\pi^+_p$ reaction at 3.65 BeV/c we have observed an enhancement in the $p\pi^+\pi^+$ system for small momentum transfer. The observed effect expresses itself as a concentration of events near $M(p\pi^+\pi^+) = 1560$ MeV if we select events with $\Delta^2(p\pi^+) < 15 \, m^2_\pi$. The effect is furthermore associated with $N^{*++}$ production. The corresponding Chew-Low plot is given in Fig. 7-1. The effect is related principally to double $N^{*++}$ formation. That is, the Dalitz plot boundary corresponding to a $p\pi^+\pi^+$ mass value of ~1700 MeV encloses the overlap region of the $N^{*++}$ bands (see Fig. 7-2). To test whether or not we are dealing with a bonafide $T=5/2$ resonance here we have carried out the calculation of $M(p\pi^+\pi^+)$ on the basis of the model $\pi^+ + p \rightarrow \rho^0 + N^{*++}$ (peripherally) with the Bose symmetrization I discussed in Section 1.

This model appears to reproduce the qualitative features observed here. Namely the propagators leading to small momentum transfer to $p\pi_1^+$ and $p\pi_2^+$ respectively give an enhancement at low $\Delta^2$ to the $p\pi^+\pi^+$ system as well. The resulting $p\pi^+\pi^+$ distribution (for $\Delta^2(p\pi^+) \leq 15$) is shown in Fig. 7-3 together with the experimental distribution.

On the other hand it is noteworthy that at this conference H. Lipkin informed me of preliminary data by G. Alexander et al. at Rehovoth that they have observed a similar $p\pi^+\pi^+$ peak at low $\Delta^2$ in the reaction $p + p \rightarrow p\pi^+\pi^-\pi^-\pi^+$ at 5.5 BeV/c. (See Fig. 7-4) It remains to be seen whether this effect can also be explained on a kinematical model or whether a $T=5/2$ state is indeed involved.
\[ \pi^+ + p \rightarrow N^{*++} (1238) + \pi^+ + \pi^- \]

\[ M^2 (p^{\pi^+ + \pi^+}) \ (\text{BeV}^2) \]

Fig 7-1
\( \pi^+ + p \rightarrow \pi^+ + \pi^- + \pi^+ + p \)

All \( \Delta^2(p\pi^+\pi^+) \)  

\( \Delta^2(p\pi^+\pi^+) \leq 15 m^2_\pi \)

\( N^*(1238) \) band

\( M^2(p\pi^+) \) (BeV)²

\( M^2(p\pi^+) \) (BeV)²

\( N^{**}(1238) \) band

MUB - 3496
\( \pi^+ p \ 3.65 \text{ BeV/c} \)
\( \Delta^2 (p\pi^+\pi^+) \leq 15 m^*_\pi \)
\( 1120 < M(p\pi^+) < 1320 \text{ MeV} \)

-Bose symmetrized matrix for \( N^* \rho \) production

(315 events)

**Fig 7-3**
ALEXANDER et al.

$pp \rightarrow p\pi^+\pi^+\pi^-n$ 5.5 GeV/c

Fig. 7-4 $M(m_{\pi^+\pi^-})$ vs $\Delta^2 = \Delta_{\text{max}}^2 - \Delta_{\text{true}}^2$
8. A Kπ Enhancement at 1430 MeV

Two days ago, I was informed by Don Miller at Berkeley that he and his co-workers have observed what appears to be a new resonance in the Kπ system at $1430 \pm 20$ MeV and $\Gamma = 100 \pm 20$ MeV. Their attention was drawn to this particular problem by a private communication stating that evidence for such an enhancement has been observed in a collaboration experiment by a number of British laboratories. The Berkeley work will be published very soon by Hardy et al. I have, however, brought two slides with me on these results. Fig. 8-1 shows the effect. The reaction in which this enhancement is produced is $\pi^- + p \rightarrow AK^+\pi^-$ and $\Sigma^-K^+\pi^-$ at 3.9 and 4.2 BeV/c. In these reactions the conventional $K^*(888)$ and this new $K^*(1430)$ occur peripherally presumably by $K^*$ and/or $K$ exchange. If one looks at the channel with $\Sigma^-$ production viz. $\Sigma^-K^+\pi^-$ one does not observe this resonance but neither is the $K^*(888)$ produced in this reaction. Here the $\Sigma^-$ does not appear to be produced peripherally. This can be understood since it would involve the exchange of a doubly-charged strange object. In the reaction leading to $\Sigma^+K^0\pi^-$ again no effect is observed in the $K^0\pi^-$ mass distribution which excludes a $T=3/2$ assignment to this new resonance.

Furthermore the experimenters have looked at the angular distribution of the decay (see Fig. 8-2). The angular distribution of the $K^*(1430)$ decay with respect to the incident direction is suggestive of the characteristic features of a d-wave which would make it a spin $2^+$ object. Although on the present data p-wave cannot be ruled out d-wave is preferred. The best quantum numbers to date seem to be $TJ^P = 1/2, 2^+$. Hardy et al further speculate whether this new resonance could be a member of an octet with spin $2^+$. The suggestion would then be to place $K^*(1430)$ the $A_2(1330)$ and the KKn enhancement at 1410 MeV in an octet. Of course, the spin in the latter case is unknown as well as the question whether it is really a resonance.
While the masses do not agree very well with the Gell–Mann–Okubo mass formula, they are however suggestive of it. The $f_0(1250)$ which comes to mind as a possible singlet in such an octet is of course way out in mass if we consider the $A_2$ as a possible member as well. (Note added in Proof. A preprint from the British group – Birmingham Glasgow, Imperial College London, Oxford and Rutherford Lab has arrived in Berkeley. They have studied the $3.5$ GeV/c $K^-p$ reaction and have observed the new $K^*$ resonance in the reaction $K^-p \rightarrow K^0\pi^-p$. They quote a mass of 1400 and $\Gamma = 160$ MeV. Their results are comparable in statistics to those of Hardy et al. and also give a preference to $J^P = 2^+$ by two standard deviations).
HARDY et al. $\pi^- p$ 3.9-4.2 BeV/c

$\Delta \pi^- K^+$
$\Sigma^0 \pi^- K^+$
351 events
$\Delta \gamma < 1.0$ (GeV/c)

$\Delta \pi^0 K^0$
61 events

$\Sigma^+ \pi^- K^0$
78 events

$\Sigma^- \pi^0 K^+$
$\Sigma^- \pi^+ K^0$
241 events

Events per 40 MeV

$M_{K\pi}$ (MeV)

1430 MeV

Fig 8-1
Fig 8-2
9. **The $K\pi$ Enhancement at 725 MeV or $K^\star(725)$**

I will now give a brief review on the present experimental situation on the "Kappa meson" or $K^\star(725)$. Although the effect had been noticed a long time ago (on the time scale of particle physics) the situation is by no means clear and much of the evidence is contradictory.

The effect was first noted by Alexander et al.\(^1,2\) (see Fig. 9-1) who obtained a rather small and narrow enhancement at $E_{K^\star} = 726 \pm 3$ MeV, $\Gamma = 20$ MeV in the reaction $\pi^- p \rightarrow \Sigma p K$ at 2.05-2.15 BeV/c. The effect does not occur in the $T=3/2$ charge mode, $K^0\pi^-$ (see Fig. 9-2). This is evidence for a $T=1/2$ assignment to the $\Lambda$. Much weaker evidence was also presented for $K\pi(747)$ in the neutral mode. As the same authors noted later the effect does not appear at neighboring energies and in fact, I understand does not appear as strongly anymore in more recent data at the same energy. The first confirmatory evidence for the $\Lambda$ was given by Wojcicki\(^3\) et al. in the reaction $K^-p \rightarrow K^0\pi^- p$ at 1.0-1.7 BeV/c. In Fig. 9-3 we see the effect: a tremendous $K^\star(890)$ peak and next to it a tiny enhancement at 723 MeV, $\Gamma < 12$ MeV. On the enlarged scale one notes the enhancement in the $\Lambda$ region; comparable fluctuations, however, are observed in neighboring regions. This evidence, taken on its own merits, is thus not very convincing.

More recently a mass enhancement in the same general region but considerably broader has been observed by Connolly\(^4\) et al. in the reactions

\[
K^- p \rightarrow \Xi^- \pi^+ K^+ \\
\rightarrow \Xi^- p K^0 \text{ at } 2.24 \text{ BeV/c.}\]

The structure has actually shown up as a competing reaction to the $\Xi^*(1530)$ resonance and is seen as a band crossing the $\Xi^*$ in the Dalitz plot in Fig. 9-4.

A peculiar property of the $\Lambda$ is that while there is very little evidence for direct production in a simple reaction like $K^+ p \rightarrow K^0\pi^+ p$ or $K^+ p \rightarrow K^+ N^*$, there is evidence for its production in more complicated processes.
leading to five particles in the final state.

Thus the CERN Group reports an enhancement in the reaction

\[ K^+ p \rightarrow K^0 \pi^+ \pi^- p \]

shown in Fig. 9-5 which occurs in particular when events with \( N^* \) formation are eliminated. This enhancement is again rather broad when compared with the original \( \kappa \) (Note added in Proof: Goshaw et al.\(^5\))

reported a \( K^+ p \) experiment carried out at 3.5 BeV/c in the Brookhaven 80-inch bubble chamber at the 1965 American Physical Society Meeting in New York. In this work they do not observe any enhancement in the \( \kappa \) region for the same reaction quoted by the CERN group. The statistical accuracy in both experiments is comparable).
Fig. 2. (a) Histogram of $M^2(K\pi)$ for all $Q = +1$ $K\pi$ systems. The shaded area represents $K^+\pi^0$ events separately. (b, c) $M^2(K\pi)$ distributions for $K^+\pi^0$ and $K^0\pi^+$ systems with $p_\pi \geq 1.90$ GeV/c. The data have been averaged over 0.04 GeV$^2$ (the resolution width) so that only every other point is independent. The curves through the data have been drawn to give approximately the correct branching ratio for the $I = \frac{1}{2}K^*(885$ MeV). The shaded areas in (b, c) correspond to $p_\pi = 1.90$ or 2.05 GeV/c.

Fig. 1. $M^2(K\pi\pi)$ distributions for $p_\pi \geq 1.90$ GeV/c. Since the ordinate represents the number of events per 0.04 GeV$^2$ (the resolution width), only every other point is independent. The shaded area indicates $p_\pi = 1.90$ or 2.05 GeV/c.
Fig. 1. (a) Plot of the $K^0\pi^-$ mass of the 4286 events from the reaction $K^- + p \rightarrow K^0\pi^- p$ at 1.0-1.7 GeV/c in 14 MeV intervals. The curve represents the phase space for the reaction proceeding 75% of the time through $K^- p \rightarrow K^- p$ and 25% through $K^- p \rightarrow K^0\pi^- p$ directly. The $K^-$ mass is taken as 890 MeV, and its width $\Gamma$ as 50 MeV. An enhancement is seen at 723 MeV of 33 events above the background curve or 45 (or 42 events above the average of the two neighbouring bins).

(b) Plot of the 680 to 800 MeV mass region in 3 MeV intervals to show the structure of the distribution around the $\pi^-$ mass. The dashed curve represents a rough estimate of the background. The resolution is 6 MeV in this region.

Fig. 9-3
2.24 GeV/c K-P interactions Connolly et al

Fig 9-4
FERRO-LUZZI et al
3 GeV/c $K^+p$ INTERACTIONS

Fig 9-5
10. **The $K^+K^+$ Enhancement at 1275 MeV**

Ferro-Luzzi et al. at CERN have been studying the reaction

$$K^+ + p \rightarrow K^+K^+\Lambda$$

(1)

at 3.0 and 3.5 BeV/c. This reaction has been very elusive for a long time. We have looked for it at 1.96 BeV/c without finding a single case and Pevsner et al. at 2.3 BeV/c found one example. This led to a cross section of $< 10\mu$b at 2 BeV/c. This was to be compared with a cross section of 50–100 $\mu$b for the corresponding reaction

$$K^-p \rightarrow K^+K^-\Lambda$$

(2)

or $K^0K^0\Lambda$

(3)

The reason for this big difference lies of course in the fact that in

(1) $K^+K^+$ corresponds to a $T=1, S=2$ state while in (2) and (3) $\phi$ formation ($M_\phi = 1020$ MeV, $T=0, S=0$) occurs and at higher energies $K\Lambda$ (1820) formation begins to occur as well (see Section 6). From the $K^-p$ data around 2 BeV/c there was thus no evidence for a low mass $K^+K^+$ resonance state. With the higher $K^+$ energies at CERN however reaction (1) begins to occur and the data on the $K^+K^+$ mass distribution indicates a distinct enhancement at 1275 MeV (see Fig. 10–1). More work will be needed to establish whether or not this is indeed a resonance.
$K^+ p \rightarrow K K \gamma$ (CERN)

$P_K = 3.0$ and $3.5 \text{ GeV/c}$

Figure 10-1
11. The $(K\Xi)^0$ Enhancement at 1410 MeV

Armenteros et al.\textsuperscript{1} observed an enhancement in the $(K\Xi)^0$ mass distribution at 1410 MeV, $\Gamma = 60$ MeV. This effect was observed in the reaction 

\[
\bar{p}p \text{ (at rest)} \rightarrow K\Xi\pi\pi
\]

This enhancement has the property that it occurs predominantly (but not exclusively) at the overlap of the two $K^*$ bands. It thus corresponds to the decay $K^*K$. Hess et al.\textsuperscript{2} have reported a similar effect in the reaction 

\[
p^- p \rightarrow K\Xi\pi N
\]

They observe an enhancement in the system $(K\Xi)^0$ at 1430 MeV, $\Gamma = 80$ MeV and do not see it in the charged system $(K\Xi)^-$ (see Fig. 11-2). This suggests the assignment $T = 0$. 
**FIG. 1** - (K_0^0 K^± \pi^+) and (K_0^0 K^± \pi^±) effective mass distribution of the K_0^0 K^± \pi^+ \pi^- events.

**FIG. 2** - Decay Dalitz plot of the (K_0^0 K^± \pi^+) resonance.

**FIG. 3** - (K_0^0 K^±) effective mass distribution of the K_0^0 K^± \pi^+ \pi^- \pi^- events.
HESS et al. \( \pi^- p \) 3.2 \( \text{BeV/c} \)

\[
\begin{align*}
K^0 K^- \pi^+, K^+ \bar{K}^0 \pi^- \\
&\quad \text{(218)}
\end{align*}
\]

\[
\begin{align*}
\Delta^2(n) &\leq 1.2 \text{ (GeV/c)}^2 \\
1430 \pm 40 \text{ MeV}
\end{align*}
\]

\[
\begin{align*}
K^0 K^- \pi^-, K^0 K^- \pi^0 \\
&\quad K_0 \bar{K}_0 \pi^- \text{ (258)}
\end{align*}
\]

\[
\begin{align*}
\Delta^2(p) &\leq 1.2 \text{ (GeV/c)}^2
\end{align*}
\]

Fig 11-2

MUB-3193
12. The ρ Puzzle

Two features about the ρ meson have been noted for a long time:

(a) The angular distribution of ρ decay in the ρ center of mass has a markedly different behavior for charged and neutral ρ mesons. In the case of charged ρ meson production leading to three particles in the final state, e.g. \( π^- + p \rightarrow π^-π^0 p \) one finds an asymmetry which changes sign as the ρ peak is traversed. This is readily understood in terms of a small amount of s-wave (and hence T=2) interference. The effect is rather insensitive to bombarding energy and is illustrated in Fig. 12-1 where the ratio \((F-B)/(F+B)\) is shown as a function of \(M(π^-π^0)\). The puzzling feature occurs for the case of neutral ρ meson production. Here the \((F-B)/(F+B)\) ratio remains positive as the ρ meson mass region is traversed and only goes to zero (or possible slightly negative) near 1100 MeV and then rises again as the \(f^0\) is traversed. This effect is illustrated in Fig. 12-2 for three particles in the final state, viz, \( π^- + p \rightarrow π^+π^- n \). Nearly the identical phenomenon occurs in our own data at 3.65 BeV/c with four particles in the final state selected according to:

\[
π^+ p \rightarrow π^+π^-N^{++} \rightarrow π^+ p
\]

(See Fig. 12-3) and in similar data at 4 BeV/c of the ABBBHM collaboration. It has often been suggested\(^{(4)}\) that this behavior can be understood in terms of an s-wave T=0 \(ππ\) resonance located right on top of the ρ meson and of similar width. This is by no means experimentally established however.

The entire picture appears to clarify at higher momenta where the peripheral model should work even better. This is illustrated in the very beautiful data
obtained in the $\pi^+p$ interaction\textsuperscript{5} at 8 GeV/c (see Fig. 12-4). In this data it looks very much as if the entire $\pi\pi$ scattering vertex is dominated by the $\rho$ and $f^0$, i.e., $p$- and $d$-wave scattering up to $M(\pi^+\pi^-) = 2.5$ BeV. If this is indeed the case it may be possible to fit the observed angular and mass distributions with a small contribution from $T=0$ s-wave a $T=2$ s-wave (from the $\pi^-\pi^0$ data) a $T=1$ p-wave (the $\rho$ meson) and a $T=0$ d-wave (the $f^0$ meson). It is important to note here that at a bombarding energy at which the $f^0$ production is kinematically not possible the tail of the resonance can already give important contributions to the $\pi\pi$ scattering amplitude. There is no evidence in the data I quoted for direct $\sigma$ production $M(\pi\pi) = 400$ MeV. This is brought out more quantitatively in the comments of W. Selove at this conference.

(b) Is there further structure to the $\rho^0$?

This too has been investigated extensively for a long time but no definite conclusion can yet be drawn. The question divides itself into two parts:

1: Is there interference with the $2\pi$ decay of the $\omega$?

2: Is there another resonance (e.g. $T=0$) with a mass falling within the $\rho$ band?

1: As far as the $2\pi$ decay of the $\omega$ is concerned Walker et al. have summarized a number of experiments showing evidence for $\omega \rightarrow 2\pi$ and concluded that the ratio $\omega \rightarrow 2\pi/\omega \rightarrow 3\pi$ is $R = 1.8^{+1.2}_{-0.6}$%. More recently this question has been scrutinized very extensively by Lütjens and Steinberger\textsuperscript{6}(LS). Their claim is that when all available data is combined all observed peaks in the region near $785$ MeV can be ascribed to statistical fluctuations and that $R = -0.003 \pm 0.008$, or $< 0.8\%$ with $90\%$ confidence. Their compilation which is shown in Fig. 12-5 gives the mass distribution $M(\pi^+\pi^-)$ from 700 to 850 MeV. On examining their data one notices a considerable difference in location in the $\rho$ peak for
class I events (which correspond principally to four particles in the final state) and class II events (which correspond exclusively to the reaction $\pi^- p \rightarrow \pi^- \pi^+ n$, i.e., three particles in the final state), namely in class I events $\rho$ peak occurs at lower mass values. LS do not comment on this point. In the four particle final states $\rho$ production tends to proceed by double resonance formation, e.g.: $\pi^+ + p \rightarrow \rho^0 + N^{*++}$. At the lower bombarding energies used in their compilation the double resonance region gets cut out in part by the kinematical boundary. This can be noted by considering the four particle phase space triangle (see Fig. 12-6). Depending on the importance of double resonance formation in the reactions contributing to the data compiled by LS this may have the effect of shifting the $\rho$ peak to lower mass values. This type of mass shift effect was observed clearly by Kadyk $^7$ et al. in the reaction $K^+ + p \rightarrow K^+ \pi^+ \pi^- p$ at 1.58 BeV/c (see Fig. 12-7 and 12-8), there the reaction appears to proceed through double resonance formation even though only the tails of the two resonances are kinematically allowed. It seems to me therefore that a detailed study of the kinematic constraints in the individual data is needed to evaluate the effect of such a mass shift on the value of $R$.

Peculiar "bumps" have been showing up in the $\rho$ distribution in many bubble chamber experiments; none, however have been statistically significant by themselves. The most remarkable evidence for a double peak was obtained by a spark chamber experiment presented by Keefe $^8$ et al. at the Dubna Meeting (see Fig. 12-9). Their data appears to be statistically rather good. The experiment will however be repeated to study the effect of systematic errors which may be associated with the use of a new instrument.

I wish to thank S. Goldhaber and B. C. Shen for help in compiling this material.
Fig 12-2

$\pi^+ p \rightarrow \eta \pi^- \pi^+$

Compilation by S.O.B. Group

$A = \frac{F-B}{F+B}$

$M(\pi^- \pi^+)$

- $2.75 \text{ GeV}/c$ (Saclay, Orsay, Bologna, Bari)
- $4 \text{ GeV}/c$ (L. Bondar et al. [12])
- $3.3 \text{ GeV}/c$ (Z. Guiragossian [8])
- $3 \text{ GeV}/c$ (V. Hagopian et al. [11])
- $6 \text{ GeV}/c$ (Heavy liquid, Veillet et al. [15])
$\pi^+ p \ 3.65 \text{ BeV/c}$

(a) $\pi^+ p \rightarrow N_{3/2}^{++} (1238) + \pi^+ + \pi^-$

1142 events

(b) $\cos \theta_p$

(c) $\frac{F - B}{F + B}$ vs. $M(\pi^+ \pi^-)$ (BeV)
AACHEN-BERLIN-CERN COLLABORATION

$\pi^+ p \rightarrow \pi^+ \pi^- (N^*)^{++}$ at 8GeV/c

**FIG 12-4**
FIG. 1. $\pi^+\pi^-$ mass distribution for Class I events. The events in this figure correspond to a total $\omega$ production of 4036. The solid curve at the bottom illustrates the expected shape for $\omega-2\pi$ decay for the average experimental resolution of this compilation. The events in this figure correspond to a total $\omega$ production of 4036. The solid curve at the bottom illustrates the expected shape for $\omega-2\pi$ decay for the average experimental resolution of this compilation.

Table II. Experiments in Class I.

<table>
<thead>
<tr>
<th>Experimental</th>
<th>Number of $\omega-3\pi$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2.03 \text{ GeV/c } \pi^- p \to \pi^- p + \pi^+ + \pi^-(+\pi^0)$</td>
<td>55</td>
<td>a</td>
</tr>
<tr>
<td>$2.1 \text{ GeV/c } \pi^- p \to \pi^- p + \pi^+ + \pi^-(+\pi^0)$</td>
<td>127</td>
<td>b</td>
</tr>
<tr>
<td>$2.75 \text{ GeV/c } \pi^- p \to \pi^- p + \pi^+ + \pi^-(+\pi^0)$</td>
<td>230</td>
<td>c</td>
</tr>
<tr>
<td>$3.7 \text{ GeV/c } \pi^- p \to \pi^- p + \pi^+ + \pi^-(+\pi^0)$</td>
<td>150</td>
<td>d</td>
</tr>
<tr>
<td>$4.0 \text{ GeV/c } \pi^- p \to \pi^- p + \pi^+ + \pi^-(+\pi^0)$</td>
<td>75</td>
<td>e</td>
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<tr>
<td>$1.76 \text{ GeV/c } \pi^+ p \to \pi^+ p + \pi^- + \pi^-(+\pi^0)$</td>
<td>369</td>
<td>f</td>
</tr>
<tr>
<td>$2.08 \text{ GeV/c } \pi^+ p \to \pi^+ p + \pi^- + \pi^-(+\pi^0)$</td>
<td>450</td>
<td>g</td>
</tr>
<tr>
<td>$2.3-2.9 \text{ GeV/c } \pi^+ p \to \pi^+ p + \pi^- + \pi^-(+\pi^0)$</td>
<td>800</td>
<td>h</td>
</tr>
<tr>
<td>$3.5 \text{ GeV/c } \pi^+ p \to \pi^+ p + \pi^- + \pi^-(+\pi^0)$</td>
<td>524</td>
<td>i</td>
</tr>
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<td>$1.23 \text{ GeV/c } \pi^- d \to \pi^- p + \pi^+ + \pi^-(+\pi^0)$</td>
<td>182</td>
<td>j</td>
</tr>
<tr>
<td>$1.51 \text{ GeV/c } K^- \Lambda \to \pi^- p + \pi^+ + \pi^-(+\pi^0)$</td>
<td>234</td>
<td>k</td>
</tr>
<tr>
<td>Stopping $\bar{p} + p \to 2\pi^+ + 2\pi^- (+\pi^0)$</td>
<td>120</td>
<td>l</td>
</tr>
<tr>
<td>Stopping $\bar{p} + p \to K^+ + \Lambda + \pi^+ + \pi^-(+\pi^0)$</td>
<td>225</td>
<td>m</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>3541</strong></td>
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Table III. Experiments in Class II.

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<td>$1.59 \text{ GeV/c } \pi^- p \to \pi^- p + \pi^- + n$</td>
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<tr>
<td>$1.7 \text{ GeV/c } \pi^- p \to \pi^- p + \pi^- + n$</td>
<td>b</td>
</tr>
<tr>
<td>$1.9-2.1 \text{ GeV/c } \pi^- p \to \pi^- p + \pi^- + n$</td>
<td>c</td>
</tr>
<tr>
<td>$2.75 \text{ GeV/c } \pi^- p \to \pi^- p + \pi^- + n$</td>
<td>d</td>
</tr>
<tr>
<td>$3.0 \text{ GeV/c } \pi^- p \to \pi^- p + \pi^- + n$</td>
<td>e</td>
</tr>
<tr>
<td>$3.7 \text{ GeV/c } \pi^- p \to \pi^- p + \pi^- + n$</td>
<td>f</td>
</tr>
</tbody>
</table>

**Fig. 12-5**
Fig 12-6
KADYK et al

\[ K^+ p \rightarrow K^+ \pi^- \pi^+ p \]

1.58 GeV/c

Fig 12-7
KADYK et al.

\[ K^+ p \rightarrow K^+ \pi^- \pi^+ p \]

All events

Events with

\( N^* (1130-1330 \text{ MeV}) \)

Fig 12-8
Dipion Mass Spectrum

\[ \pi^- p \rightarrow \pi^+ \pi^- \text{ MM} \]

\[ -\Delta^2 \geq 9\mu^2 \]

Events

Dipion Mass in MeV

Fig 12-9

MUB-3405
REFERENCES

The $\pi^0$ Enhancement Leading to $A_1$ and $A_2$


REFERENCES (continued)

2. The $\pi\omega$ Enhancement or "B" Meson


3. The $\chi^0(960)$ Resonance or $\eta'(960)$


4. The $\pi^+\pi^-\pi^0$ Enhancement at 975 MeV or H Meson

5. The $K\pi$ Enhancements

5-1 This entire subject was summarized by Rafael Armenteros at the 1964 Dubna Conference.


6. The $\Xi^-(\Xi^+(1820))$


REFERENCES (Continued)

7. The ππ Enhancement at 1560 MeV

8. A Κπ Enhancement at 1430 MeV

9. The Κπ Enhancement at 725 MeV or Κ

10. The K ± K Enhancement at 1275 MeV
REFERENCES (continued)

11. The $K^0\bar{\Lambda}$ Enhancement at 1410 MeV


11-2 See Ref. 1-10.

12. The $p$ Puzzle


12-2 See Ref. 1-4


12-4 A recent calculation is given by L. Durand III and Y. T. Chiu (preprint).

12-5 See Ref. 1-7.


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