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THE SEARCH FOR HYPERONS AND BOSONS BELONGING TO HIGHER SYMMETRIES

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I. Introduction

As is well known, all particles and resonances that are well established so far fall into the groups of singlets, octets and decuplets in SU. What I want to discuss today is the question "To what extent has evidence been found for the existence of higher-symmetry groups?" It is particularly attractive to look at the question of what is involved if higher-symmetry groups exist in terms of the quark picture. Since this was designed to express the existing particles which fall into octets and decuplets, it is not surprising that the presence of higher symmetries such as the group of 10 and 27 would require a more complex quark structure. So far we know two types of quark structures; the boson, consisting of qq, and the baryons, consisting of three quarks, qqq. We realize, of course, that the quark picture must not be taken too literally, and that very likely it is just a mathematical tool. All the same it helps to clarify the ideas about higher-symmetry groups. Thus if we want to form a boson with I = 2 such as π⁺π⁺, or a boson of I = 1 and S = 2, such as K⁻K⁺, or a boson of I = 3/2, such as K⁺π₀π⁺, we need a more complex quark structure, namely qqqq. Furthermore, we can ask whether structures like p π⁺π⁺, an I = 5/2 baryon, exist, or, alternatively, the structures K⁺p or K⁺n, which would be Y = 2, I = 1 or 0. Here again to form such structures we need at least four quarks and an antiquark, qqqq. That this is so can be seen readily for the positive-strangeness hyperons. To obtain positive strangeness we need at least one antilambda quark, Ł. To get a hyperon we need three quarks, thus the total structure must consist of four quarks and one antiquark. From the fact that so far two quark structures are known, namely the bosons (qq) and baryons (qqq), it does not necessarily follow that these more complex structures should also exist. We have to appeal to experiment to find out whether they do or not.

The present experimental situation can be summarized by saying that there is no conclusive evidence for the existence of any such resonances. The strongest candidate, perhaps, is the K⁺n I = 0 state discovered by Cool and co-workers, which is a clear bump in the K⁺n cross section. The question whether this bump is a resonance or not is, however, not settled yet. We may next ask, What is the cause for the present experimental picture? It seems to me that there are at least three alternatives:

(a) Such higher quark structures do not exist.
(b) Such structures exist; however, their formation cross sections are less by one or two orders of magnitude than the formation cross sections of simpler quark structures.
(c) Such structures exist and are formed with comparable coupling constants; however, there are selection rules which forbid their formation in the usual reactions studied so far.
I will next review the experimental situation. I will discuss the following topics:

II. Does a $K_1T_1T_I = 3/2$ state exist?

III. Does a $K^+K^+ I = 1, S = 2$ state exist?

IV. The $p\pi^+\pi^+$ mass peak at 1560 MeV or a study in "reflections."

V. The search for positive-strangeness hyperon resonances.

II. Does a $K\pi\pi$ $I = 3/2$ State Exist?

I will be very brief on the $K\pi\pi$ $I = 3/2$ system, because it has been reviewed a number of times already. The basic point is that a mass peak at 1270 MeV has been observed in the $I = 3/2$ $K\pi\pi$ system in a $\bar{p}p$ annihilation experiment at 3 BeV/c. This peak appears to decay into $K^*$ and, to some extent, into $Kp$. The effect is one of $\geq 3.5$ standard deviations. On the other hand, no confirmation was obtained in an experiment of $\bar{p}p$ annihilations at 3.7 BeV/c. A number of experiments on $Kp$ interaction which could in principle also lead to such a state have not shown any evidence for an $I = 3/2$ state, although there is some evidence for an $I = 1/2$ $K\pi\pi$ state at 1270 MeV. See Figs. 1 through 3. This is where the matter stands at present, and I feel that a repetition with good statistics of the 3-BeV/c $\bar{p}p$ experiment would be advisable to settle this matter once and for all. To summarize, I feel there is at present no convincing evidence for the presence of an $I = 3/2$ $K\pi\pi$ state.

III. Does a $K^+K^+$ $I = 1, S = 2$ State Exist?

A compilation of the then available data was presented by Palmer at the 1966 High Energy Conference at Berkeley. We have added some further data from our experiment (Shen et al.). The conclusion is that no clear peak is observable in the combined data.

Some evidence for a $K^*K^+(1280)$ enhancement has been observed by a group at CERN, in the reactions

$$K^+p \rightarrow K^+K^+\Lambda,$$
$$K^+p \rightarrow K^+K^+\Sigma^0,$$
$$K^+p \rightarrow K^+K^0\Sigma^+,$$

as well as

$$K^+p \rightarrow K^+K^+\Lambda\pi^0,$$
$$K^+p \rightarrow K^+K^0\Lambda\pi^+.$$

However, data from more extensive recent work at Wisconsin and Brookhaven do not show any such enhancement. See Figs. 4 and 5. Here I may note in passing that the four-particle final states show evidence for $K^*(890)$ formation as well as possible higher $N^*$ decay into $\Delta K$ or $\Sigma K$.

IV. The $p\pi^+\pi^+$ "Mass Peak" at 1560 MeV or a Study in "Reflections"

I stated here already, two years ago, that we felt that the $p\pi^+\pi^+$ peak at 1560 MeV reported earlier by us was some type of kinematical
$pp, 3 \text{ BeV/C}; \text{CERN-E.P. Paris-I.C. London}$

\[ K^0, K^+ \pi^+ \pi^- \pi^0 \]

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

\[ a) K^+ \pi^- \pi^+ \pi^- \]

\[ b) K^+ \pi^- \]

\[ T_z = \pm \frac{3}{2} \]

\[ \text{FROM } p-p \rightarrow K^{*} K^{*} \pi^{+} \pi^{-} \pi^{0} \text{ AT } 3.7 \text{ Bev/c} \]

\[ 360 \text{ EVENTS} \]

\[ (4 \text{ COMBINATIONS/EVENT}) \]

\[ \text{Yeh et al.} \]

\[ \text{M}_{\text{KNN}} \text{ (MeV)} \]

\[ 830 \leq M_{K^0} \leq 945 \text{ MeV} \]

\[ (531 \text{ COMBINATIONS}) \]

\[ \text{XBL 672-549} \]

\[ \text{Fig. 1} \]
$K^+ p$, 4.6 BeV/c; Shen et al.

(a) $K^+ p \rightarrow (K^*\pi)^0 N^{*++}$
(b) $K^+ p \rightarrow (K^*\pi)^0 N^{*++}$
(c) $K^+ p \rightarrow (K^*\pi)^+ N^{*+}$
(d) $K^+ p \rightarrow (K^*\pi)^++ N^{*0}$

759 events
442 events
135 events
182 events

Fig. 3
Fig. 4
$K^+ p \rightarrow K^+ K^+ \Lambda \pi^+$, $K^+ K^+ \Lambda \pi^+$, $K^+ K^+ \Sigma^+ \pi^+$

- LRL
  - 4.6 GeV/c

- CERN
  - 3.0, 3.5, 5 GeV/c

- BNL
  - 3.0 GeV/c

Combined 311 events

Fig. 5
enhancement. The issue was clouded, however, by the fact that two \( \pi^+ \) mesons were involved and that \( N^{*++} \) formation with each \( \pi^+ \) appeared to be associated with this peak. An elaborate series of calculations by Dash et al.\(^9\) was, however, able to reproduce the qualitative features of this peak. In these calculations we evaluated the matrix elements for the reaction \( \pi^+p \rightarrow N^* + \rho \) for a number of models by a Monte Carlo technique. These models are:

1. Breit-Wigner amplitudes for the resonances and a pion propagator for the exchange particle.
2. Complete matrix element with exchange particles set on the mass shell in the spin factors.
3. Complete matrix element with all momenta treated as unit vectors.
5. Complete matrix element together with the introduction of a form factor.

Here the numerals correspond to the curves in Figs. 6 and 7.

As we proceeded from one approximation to the next we found in general that the calculations resembled the overall features of the experimental data, which indicate that the model is not too far off. However, in approximation 4, where we have evaluated the complete matrix element, we get a result which no longer resembles the experimental data. This feature is strongly reminiscent of the difficulties experienced in other calculations with exchange diagrams—namely, that when the complete spin factors for the resonances are introduced, the powers of momentum transfer squared, in the numerator, become so large that the calculations begin to deviate from the experimental data. In particular such a model gives a completely wrong dependence on momentum transfer. This difficulty has in general been attacked by the introduction of form factors\(^10\) or absorption effects,\(^11\) or both. Here, too, we have introduced the form factor

\[ F(\Delta^2) = \frac{(\Delta^2 - M_{\pi}^2)}{(\Delta^2 + \Lambda^2)}, \]

which has served us reasonably well in earlier calculations,\(^12\) and this gives us approximation 5. Although all indications seem to point in the direction that absorption effects\(^11\) are the more correct approach to this difficulty, the introduction of the form factor gives a reasonable behavior with momentum transfer, and is used here more in the sense of a phenomenological factor.

What is new in this field is that by our study of the \( K^+p \) interaction at 4.6 BeV/c we have found an analogous peak in the \( p\pi^+K^+ \) system. However, before anyone suggests that this is another member of the 35 group, let me hasten to add that the explanation for the effect is now completely clear and rather trivial in nature. Namely, the effect is the reflection of the decay alignment of the appropriate vector meson. This simple interpretation was earlier advocated by Morris Fripstein.\(^13\) The reactions studied are

\[ \pi^+p \rightarrow \pi^+\pi^-N^{*++} \quad \text{at 3.65 BeV/c}, \]
\[ K^+p \rightarrow K^+\pi^-N^{*++} \quad \text{at 4.6 BeV/c}. \]

The \( p\pi^+\pi^+ \) peak was then observed when events with forward \( \pi^- \) production
\pi^+ p, 3.65 \text{ BeV/c}; \text{ curves by Dash et al.}

\Delta^2_{\pi^-} \leq 15 M^2_{\pi^-}

315 \text{ events}

Fig. 6
Fig. 7

$2.56 \text{ BeV} \quad \pi^+ p, 3.65 \text{ BeV}/c; \text{ curves by Dash et al.}$

$N^{*-+} \rho^0 \text{ filter, 565 events}$

$1.56 \text{ BeV}$

$M^2_{p\pi^+\pi^+} \text{(BeV)}^2$

Fig. 7
were selected. What apparently happens in reality can be approximated by a very simple idealized model illustrated in Fig. 8. Namely, by selecting forward \( \pi^- \) production, which primarily comes from \( \rho \) decay, we are choosing events with the configuration depicted in the figure, which gives rise to a well-defined \( \pi^-\pi^+ \) mass peak. This mass depends on the incident energy, and for 3.65 BeV/c it turns out to be \( \approx 1540 \) MeV. It so happens, however, that for a \( \pi^-\pi^+ \) mass of \( \approx 1540 \) to 1580 MeV both \( \pi^-\pi^+ \) combinations fall in the \( N^{*++} \) band. It is this feature which had clouded the issue and had led us in the initial work to reject this simple interpretation. We can carry out the calculation for the \( K^+p \) reaction in an analogous fashion. Here again we get a well-defined \( \pi^+K^+ \) mass peak at 2180 MeV. Furthermore, we can also see the peak in the \( \pi^+\pi^- \) mass distribution corresponding to forward \( \pi^- \) and \( K^+ \) respectively. The details are summarized in Table I. See Figs. 9 and 10.

Table I. Three-particle mass peaks due to kinematical reflection of the vector meson alignment and peripheral production.

<table>
<thead>
<tr>
<th>Case I.</th>
<th>Computed</th>
<th>Experimental</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \langle \cos \theta_{\pi^-} \rangle )</td>
<td>( M(\pi^+\pi^-) )</td>
<td>( M(\pi^+\pi^-) )</td>
</tr>
<tr>
<td>0.8</td>
<td>1.54</td>
<td>1.56</td>
</tr>
<tr>
<td>-0.8</td>
<td>2.52</td>
<td>2.56</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case II.</th>
<th>Computed</th>
<th>Experimental</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \langle \cos \theta_{\pi^-} \rangle )</td>
<td>( M(\pi^-) )</td>
<td>( M(\pi^-) )</td>
</tr>
<tr>
<td>0.8</td>
<td>2.18</td>
<td>2.14</td>
</tr>
<tr>
<td>-0.8</td>
<td>2.90</td>
<td>2.94</td>
</tr>
</tbody>
</table>

V. The Search for Positive-Strangeness Hyperon Resonances

Ever since the first experiments on the interaction of positive and negative \( K \) mesons with nuclei in emulsions, a vast difference was observed in the behavior of these interactions. Although the negative \( K \) mesons led to hyperon production—lambda, sigma, and later on, cascade—the positive \( K \) meson interactions led to no such states. This
Fig. 8

**SELECT**

\[ \Theta \approx 0^\circ \]

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

3.65 GeV/c

**SELECT**

\[ \Theta \approx 0^\circ \]

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

4.6 GeV/c
\[ K^+ p \rightarrow K^+ \pi^- \pi^+ p \] 4.6 \text{ GeV/c} 

(a) \( N^{**} \) in 1292 events

\[ \cos \theta(\pi^-) \geq 0.8 \]

(b) \( K^{*0} N^{**} \) in 493 events

\[ \cos \theta(\pi^-) \geq 0.8 \]

**Fig. 9**
\[ K^+ p \rightarrow K^+ \pi^- \pi^+ p \quad 4.6 \text{ Bev/c} \]

(a) \( N^{++} \) in, 1292 events

\[ \cos \Theta(K^+) \geq 0.8 \]

(b) \( K^{*0} N^{++} \) in, 493 events

\[ \cos \Theta(K^*) \geq 0.8 \]

Fig. 10
difference was readily understood in terms of the strangeness concept introduced by Gell-Mann and Nishijima. With the advent of \( Y^* \) resonances, the question can again be raised whether hyperon resonances of positive strangeness exist also.

It has been known for some time that the \( K^+p \) cross section has an extremely simple structure. It starts out at about 10 mb and continues up very slowly to about 12 mb at 800 MeV/c. At this point the cross section rises sharply to about 18 mb at 1250 MeV/c. From this point on, it continues smoothly out to a level of about 18 mb until 20 BeV/c, the highest measured point so far. The \( K^+d \) cross section is quite similar, running more or less parallel to the \( K \)-hydrogen cross section at about twice the height. Furthermore, studies have been made of the \( K^+N \) effective-mass distributions in various final states, in an attempt to find a \( K^+N \) resonance in the \( I = 0 \) or \( I = 1 \) state, but all of these have been to no avail so far, up to masses of 1.8 BeV. In this energy region no resonance effects were observed. It was also known that the rise in the \( K^+p \) cross section from the 12 mb level to the 18 mb level was primarily associated with inelastic processes, namely, single-pion production, which proceeds at first through \( N^*K \) production and then at higher energies through \( K^+N \) production as well.

V.A. The Experiments of Cool et al.

About two and a half years ago we started a series of experiments in the \( K^+p \) and \( K^+d \) systems to investigate this region in detail. This was the situation until eight months ago, when a series of very accurate measurements by Cool, Giacomelli, Kycia, Leontic, Li, Lundby, and Teiger showed that there was actually more structure to these cross sections. They found peaks in the \( K^+p \) as well as the \( K^+d \) cross sections in the region of the rapid change of these cross sections.

It has been speculated that these peaks may be due to the presence of two new resonances with the following properties:

<table>
<thead>
<tr>
<th>&quot;Enhancements&quot;</th>
<th>Reac-</th>
<th>( P_K )</th>
<th>Mass</th>
<th>Width</th>
<th>( \sqrt{S} )</th>
<th>(J, +1/2)</th>
<th>SU3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Z^0 )</td>
<td>( K^+d )</td>
<td>1.15</td>
<td>1863</td>
<td>150</td>
<td>0 2 1 8</td>
<td>0.55</td>
<td>( \Lambda )</td>
</tr>
<tr>
<td>( Z^1 )</td>
<td>( K^+p )</td>
<td>1.25</td>
<td>1910</td>
<td>180</td>
<td>1 2 1 4</td>
<td>0.31</td>
<td>27</td>
</tr>
</tbody>
</table>

The question is now to determine whether these two peaks in the \( K^+p \) and \( K^+d \) systems are indeed resonances or some other type of effect.

In Fig. 11 are shown the data of Cool et al. on the \( K^+p \) interaction, which indicated the \( I = 1 \) peak. Figure 12 shows their data in the \( K^+d \) interaction, showing the presence of the \( I = 0 \) peak. Figure 13 shows the \( K \)-neutron interaction obtained by subtracting the \( K \)-proton cross section from the \( K \)-deuteron cross section and letting for the Glauber correction. Finally, Fig. 14 shows the pure \( I = 1 \) and \( I = 0 \) cross sections obtained by unfolding the important effects of the internal momenta of the nucleons in deuteron.
Fig. 11

\[ \sigma_{\text{tot}}(K^+ p) \]

- GOLDBHABER et al.
- BARASHENKOV et al.
- COOK et al.
- COOL et al.

\( \rho_{K\text{lab}} \) (GeV/c)
Fig. 12
Fig. 13
Cool et al.

Fig. 14.
V.B. The Experiments of Bland et al. on the K⁺p System

When the data of Cool and co-workers became available, we were in the process of studying a series of bubble chamber pictures taken in the region where the K-hydrogen and K-deuterium cross sections were known to change radically, namely in the region from 860 to 1580 MeV/c. The people involved in various aspects of this work are R. W. Bland, M. G. Bowler, J. L. Brown, Sulamith Goldhaber, A. A. Hirata, J. A. Kadyk, B. C. Shen, V. H. Seeger, G. H. Trilling, C. Wohl, and me.15

Our data on the K-hydrogen system are fairly extensive, whereas the data on the K-deuterium system are still only preliminary. In the study of the K⁺p system, we have essentially completed the momenta 860, 960, 1200, 1360, and 1580 MeV/c, leaving a few intermediate momenta to be completed. Where applicable we have included in our compilations the published work of Kehoe (910 MeV/c)16 Boldt et al. (1140 MeV/c),17 and Bettini et al. (1450 MeV/c),18 as well as work on K⁺p and K⁺d reactions at other momenta--200 to 800 MeV/c, 1960 MeV/c, and 2300 MeV/c—in which some of us participated several years ago.19-21

The following series of figures illustrates our results. Figure 15 shows the various inelastic cross sections we have measured in the K⁺p system. The curves shown are just freehand drawings used to connect the points, and have no further significance. The upper curve is the total inelastic cross section, with the three KNπ channels below; K⁺pπ⁺ is the most abundant channel, followed by K⁺pπ⁰ and K⁺π⁻n. The two-pion production also begins to appear at these momenta, and is shown as the lowest curve. The N* threshold, which occurs first, and the K* threshold are also indicated. The two dashed lines correspond to the unitarity limits for J = 1/2 and J = 3/2. As we see, the total inelastic cross section reaches the unitarity limit for a J = 3/2 wave at about 1100 MeV/c. I want to come back to this point later.

Figure 16 shows the Dalitz plots for the various momenta we have investigated. This graph illustrates the feature that we have N* production at all these momenta from 860 MeV/c on up; however, that K* production becomes important only at around 1100 MeV/c. The K* band is shown as the vertical band on this plot. Another feature that occurs is illustrated in Fig. 17, namely, we find very considerable interference between the K* production, the vertical band, and the N* production here. On the right side we show a square in the N*K* overlap region and its three mass-conjugate regions. Assuming no interference and using the fourth square to correct for background, we expect

N(overlap) = 200 + 116 - 45 = 271 events,

compared with 444 events observed. There is an excess of six standard deviations in the overlap region, clearly indicating constructive interference. We have done an analysis of the Dalitz plot density,22 assuming N* and K⁺p wave-production amplitudes and an incoherent background. This model gave a good fit to the Dalitz plot density, and indicated that the interference, although constructive in the overlap region, becomes destructive in other parts of the Dalitz plot and gives no appreciable net contribution to the cross section. Furthermore, even if the dynamical assumptions of the model are incorrect, we estimate the maximum contribution to the cross section from interference...
Fig. 15

KN T=1 Inelastic cross sections

Thresholds

Unitarity limits

$\sigma$ (Inelastic)

$\sigma (K^0 p \pi^+)$

$\sigma (K^0 p \pi^0)$

$\sigma (K^+ p \pi^0)$

$\sigma (K^+ \pi^+ \pi^-)$

$\sigma (K^+ \pi^+ n)$

Beam momentum (BeV/c)
Bland et al.

\[ K^+ p \rightarrow K^0 \pi^+ \ 860-1580 \text{ MeV/c} \]

**Fig. 16**
$K^+ p \rightarrow K^0 p \pi^+$

1200 MeV/c

$M^2_{p\pi^+}$

$(\text{BeV})^2$

$M^2_{K^0\pi^+}$

$(\text{BeV})^2$

Fig. 17
to be ~1 mb, and thus not adequate to explain the peak observed by Cool et al.

Figure 18 again shows our cross-section data, this time compared with the results of Cool et al. The upper curve is the data of Cool et al., where the errors are not shown but are about two to three times the width of the curve. Here we have grouped our inelastic events according to $K^*N$ production and $KN^*$ production as well as the total $KnN$ inelastic cross section. The dashed curve corresponds to the elastic cross section, which we also measure directly. All these cross sections, incidentally, are normalized to Cool's cross sections, a method which is considerably more accurate than the normalization to $\pi$ mesons.

There are two noteworthy features on this graph. First of all, we see that the peak observed by Cool et al. corresponds primarily to the peak we observed in the $KN^*$ system. Here it must be noted, however, that the $KN^*$ peak probably occurs at a somewhat lower momentum (~100 MeV/c). Secondly, we see no obvious variation in the elastic cross section corresponding to the Cool peak. Thus, as these authors have already pointed out, if this effect is a resonance, it is an extremely inelastic resonance. Of course, there should always be some reflection in the elastic cross section, and within our errors we cannot rule out a small effect of the order of $1/2$ mb or so in the region of this peak.

Now that we have established the fact that the $I = 1$ peak corresponds primarily to $KN^*$ production we will examine this channel in greater detail. We find that the $N^*$ production angular distribution has a predominant $\sin^2\theta$ term together with some forward peaking due to interference terms. This is shown in Fig. 19 for the 1200-MeV/c data as an example. At other momenta studied the distributions have the same general characteristics, with an increasing amount of forward peaking as the momentum increases. This behavior is summarized in Fig. 20, where we give the coefficients for these distributions in a Legendre polynomial expansion at the various momenta. There the shape of $A_0$ is just a reflection of the cross section for $KN^*$ production. The pronounced variation in $A_0$ probably just reflects the $\sin^2\theta$ nature of the angular distribution. There is no rapid variation in any of the odd coefficients, which arise purely from interference terms. In particular, $A_1$ increases steadily and monotonically from threshold.

Next we can study the decay angular distribution of the $N$ in the $N^*$ center of mass. The angles are defined in Fig. 21, and the angular distribution in $|\cos\gamma|$ and $\delta'$ are given in Fig. 22, again for the 1200-MeV/c data. Here $\gamma$ is the angle between the $N^*$ decay direction and the production normal in the $N^*$ center of mass, and $\delta'$ is the azimuthal angle around the normal in the overall center of mass system. Figure 23 gives the expansion of these distributions for the various momenta we have studied. The open circle is a value from the literature I have cited. The full circles represent our data. Here, too, there is no rapid variation in the region of the Cool peak. It should also be noted that this same behavior in production and decay angular distributions continues on to the highest energies studied so far. Thus, at 1.96 BeV/$c$, and in particular in the work of the Bruxelles-CERN collaboration at 3, 3.5, and 5 GeV/$c$, the same general features are still observed.
K⁺p Cross sections

\[ \sigma_{total} - \text{Cool et al.} \]

642 MeV/c - Goldhaber et al.
810 MeV/c - Stubbs et al.
1140 MeV/c - Boldt et al.
1450 MeV/c - Bettini et al.
1960 MeV/c - Goldhaber et al.
860, 960, 1200, 1360, 1580 MeV/c - Bland et al.

Cross section (mb)

Beam momentum (BeV/c)

Fig. 18
Fig. 19

- Magnetic dipole
- Magnetic dipole with absorption of $P_{3/2}$
- Magnetic dipole with equal absorption of $P_{3/2}$ and $P_{1/2}$

17% background folded in

Events

$\cos \theta$

Magnetic dipole

Magnetic dipole with absorption of $P_{3/2}$

Magnetic dipole with equal absorption of $P_{3/2}$ and $P_{1/2}$

17% background folded in

1200 MeV/c
$K^+ p \rightarrow K N^*$

$$\frac{d\sigma}{d\Omega}(N^*) = \sum_{i} A_i P_i (\cos \Theta)$$

**Figure 20**

**Beam momentum (BeV/c)**

**MU 13596**
\[ \hat{n} = \hat{a} \times \hat{c} \]

Resonance Center-of-Mass System

Fig. 21
1200 MeV/c

- Magnetic dipole
- Magnetic dipole with absorption of $P_{3/2}$
- 17% background folded in

Fig. 22
\[
\begin{align*}
K^+ p &\rightarrow K^0 N^{*++} \\
W(\cos \theta) &= 1 + A \cos^2 \theta \\
W(\delta') &= 1 + B \sin 2\delta' + C \cos 2\delta'
\end{align*}
\]
V.C. The Approach of Trilling and Bland

It has been known for some time that the qualitative features of the production and decay angular distributions in the KN* channel agree with the predictions of the Stodolsky-Sakurai magnetic dipole p-exchange model, based on the p-photon analogy. On the other hand, if we want to look for a possible KN* resonance we must do a partial-wave analysis in this channel. Trilling has carried out the partial-wave expansion and made a rough fit to the data. The results indicate a dominance of $P_{1/2}$ and $P_{3/2}$ waves at lower momenta, with the asymmetry due to a wave of opposite parity which comes in rapidly with increasing momentum. We can compare this with a partial-wave decomposition of the magnetic dipole amplitude. Here, too, the dominant waves near threshold are $P_{1/2}$ and $P_{3/2}$, with D waves entering increasingly with increasing momentum, giving the forward asymmetry. The M1 model predicts the $P_{1/2}$ and $P_{3/2}$ waves in the ratio 1:5, while the data indicate a ratio nearer to 1:1. However, the predicted phase between the $P_{1/2}$ and $P_{3/2}$ waves and the D waves agrees with the data. This suggests that the N* production—which presumably is responsible for the peak observed by Cool et al.—can be understood largely in terms of the Stodolsky-Sakurai model. Here it must be noted that the P-wave amplitudes may be important in the K*N channel, as well as in the KN* channel. Thus these waves may be approaching their unitarity limits in the energy region of the Cool bump. This could possibly be the reason for the dropping off of the KN* cross section above 1200 MeV/c.

V.D. K*p Elastic Scattering--The Data of Wohl et al.

We have furthermore studied the K*p elastic-scattering differential cross section. Here we find that the distributions which were essentially isotropic at low momenta—except for constructive interference with the repulsive K*p Coulomb potential—become anisotropic and go over with increasing energy to a shape corresponding to diffraction scattering in the forward direction. The transition appears to occur rather smoothly and does not show any sharp break at 1200 MeV/c. This is illustrated in Figs. 24 and 25. Figure 26 gives the variation of the relevant Legendre coefficients with momentum.

We are in the process of carrying out a phase-shift analysis on the elastic scattering data. If we consider the solution with the large negative S-wave phase shift which was predominant in the low-momentum work (up to 810 MeV/c), we find that this phase levels off at about -40 deg while other higher waves start coming in, none with very large contributions, however. We have not had time so far to examine all the various alternative solutions and draw any definite conclusion from the analysis. It must be remembered here, however, that if we are dealing with a resonance it is a highly inelastic resonance and hence its phase shift will go through 0 deg rather than 90 deg.

To summarize, the picture that emerges is the following:

(a) The peak in the I = 1 KN scattering cross section is primarily due to the behavior of the KN* channel.
(b) No drastic changes occur in production or decay angular distribution as the region of the I = 1 peak is traversed.
(c) In a partial-wave expansion of the KN production channel the $P_{1/2}$ and $P_{3/2}$ waves dominate the region around 1200 MeV/c beam.
K\(^+\)p elastic scattering

\[ \frac{d\sigma}{d\Omega} \] (mb/sr)

- 860 MeV/c
- 960 MeV/c
- 1200 MeV/c
- 1455 MeV/c

(Bettini et al.)

Fig. 24
Chinowsky et al.; 1.96 BeV/c

**K^+ p elastic**
636 events

**Momentum transfer squared, t (BeV/c)^2**

**Cos \( \theta_{c.m.} \)**

**Number of events**

**\( d\sigma/d\Omega \) (mb/sr)**

**\( d\sigma/d\Omega \) (mb/sr)**

**Extrapolated**

**Fig. 25**
K⁺p elastic scattering

Expansion coefficients of $d\sigma/d\Omega = \sum a_n P_n (\cos \theta)$

- $a_0$
- $a_1$
- $a_2$
- $a_3$
- $a_4$
- $a_5$

K⁺ lab momentum (BeV/c)

Fig. 26
momentum, with neither one exhibiting rapid phase variation in this region. Thus, no single Breit-Wigner resonance amplitude appears to be responsible for the observed peak.

V.E. The Study of the $K^+d$ Interaction--the Data of Hirata et al.

As mentioned above, we are studying the $K^+d$ interaction in a series of bubble chamber exposures from 860 to 1580 MeV/c. The reactions are

$$K^+d \rightarrow K^+d \quad \text{Identifiable}$$

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Identifiable</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rightarrow K^+pn$</td>
<td>yes (1)</td>
</tr>
<tr>
<td>$\rightarrow K^0pp$</td>
<td>yes (2)</td>
</tr>
<tr>
<td>$\rightarrow K^{0+}p$ (n)</td>
<td>yes (3)</td>
</tr>
<tr>
<td>$\rightarrow K^{++}n$ (n)</td>
<td>no (4)</td>
</tr>
<tr>
<td>$\rightarrow K^{0+}n$ (p)</td>
<td>yes (5)</td>
</tr>
<tr>
<td>$\rightarrow K^{++}p$ (p)</td>
<td>no (6)</td>
</tr>
<tr>
<td>$\rightarrow K^{0+}p$ (p)</td>
<td>yes (7)</td>
</tr>
<tr>
<td>$\rightarrow K^{++}p$ (p)</td>
<td>yes (8)</td>
</tr>
</tbody>
</table>

This work is progressing, but so far our data are still preliminary. The $K^+n$ charge exchange (Reaction 3) and one $K^+n$ inelastic channel (Reaction 10) are shown in Fig. 27. What is emerging from these data is that the $I = 0$ peak must, to a considerable extent, occur in the elastic or "quasi-elastic" channels, or both (Reactions 1 and 2). The charge-exchange data on which we also show the earlier points up to 810 MeV/c of Slater et al. and the point of Butterworth et al. at 2.3 BeV/c show a rather broad peak which begins to fall off in the region of the $I = 0$ bump. Although this peak is perhaps the most promising candidate for a resonance, we are not in a position to draw any definite conclusions as yet.

V.F. The Search for the $I = 1$ and $I = 0$ Peaks in Production Experiments

In our $K^+p$ experiment at 4.6 BeV/c (Shen et al.) we have looked at various $K\pi\pi N$ and $K\pi\pi N$ reactions for evidence of the $K\pi N$ mass peaks observed by Cool et al. Many of these channels are rather complicated, but the two mass regions lie at the leading edge of the $K\pi N$ masses. We do not observe any specific peaks, and in Table II we quote upper limits for the production cross sections of such states.

In Fig. 28 we show the Dalitz plot for $K^{0+}p$ production and indicate the region in which the $KN I = 0$ and $I = 1$ bands are expected.
$K^+d$ interactions; Hirata et al.

$\sigma_{\text{tot}}(K^+n)$

Cool et al.

$K^+n \rightarrow K^0p$

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

Cross section (m.b.)

$K^+$ laboratory momentum (GeV/c)

Fig. 27
Fig. 28

Location of \( T=1, T=0 \) KN bands

\[ K^+ p \rightarrow K^0 \pi^+ p \quad 4.6 \text{ GeV/c} \]

468 events

\[ M^2(K^0\pi^+) \text{ (GeV)}^2 \]

\[ N^{*+} \]

\[ K^{*+}(890) \]

With \( N^{*+} \), \( K^*(890) \), and \( K^*(1430) \) out

PHASE SPACE

Number of events per 0.5(BEV)
Table II. Search for $I = 1$ and $I = 0$ peaks in a production experiment in the 4.6-BeV/c $K^+$ mesons.

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>I Spin</th>
<th>Upper limit on cross section (ub)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(I) Reactions $K^+p \rightarrow K^+\pi^-\pi^+p$, $K^0_{\pi^+\pi^-\pi^+p}$, $K^0_{\pi^+\pi^-\pi^+n}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K^+\pi^-p$</td>
<td>0,1</td>
<td>11</td>
</tr>
<tr>
<td>$K^0_{\pi^+p}$</td>
<td>1</td>
<td>32</td>
</tr>
<tr>
<td>$K^0_{\pi^-p}$</td>
<td>0,1</td>
<td>20</td>
</tr>
<tr>
<td>$K^0_{\pi^+n}$</td>
<td>0,1</td>
<td>10</td>
</tr>
<tr>
<td>(II) Reactions $K^+p \rightarrow K^+\pi^-\pi^+p$, $K^0_{\pi^+\pi^-\pi^+p}$, $K^0_{\pi^+\pi^-\pi^+n}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K^+\pi^-p$</td>
<td>0,1</td>
<td>11</td>
</tr>
<tr>
<td>$K^+\pi^-p$</td>
<td>1</td>
<td>7</td>
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<tr>
<td>$K^0_{\pi^-p}$</td>
<td>1</td>
<td>7</td>
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<tr>
<td>$K^0_{\pi^+p}$</td>
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<td>11</td>
</tr>
<tr>
<td>$K^0_{\pi^+n}$</td>
<td>1</td>
<td>14</td>
</tr>
<tr>
<td>$K^0_{\pi^+n}$</td>
<td>1</td>
<td>11</td>
</tr>
</tbody>
</table>

In Figs. 29 through 31 we show triangle plots for reactions

$$K^+p \rightarrow K^+\pi^-\pi^+p$$  (1)
$$\rightarrow K^0_{\pi^+\pi^-\pi^+p}$$  (2)
$$\rightarrow K^0_{\pi^+\pi^-\pi^+n}$$  (3).

Figure 29a shows the main mode with $K^{*0}$ and $N^{*++}$ formation for Reaction 1. Figure 29b shows the $K^+p$ mass versus $\pi^+\pi^-$ mass distribution, and Fig. 29c the same with $N^{*++}$ and $K^{*0}$ removed. An $I = 1$ Kp state produced in the inelastic process should show up as a band where indicated in the figure. None is observed. Here, of course, we must remember that the $I = 1$ peak is particularly highly inelastic, and thus not much is expected to show up in the Kp channel. Figures 30 and 31 show similar plots for Reactions 2 and 3. Here in Reaction 2 the $I = 0$ KN state can also show up, which is not as highly inelastic, while for Reaction 3 only the $I = 1$ KN state can occur. In Reactions 1 and 2 one would actually expect the KN states to occur together with $p$ formation. No measurable enhancement is observed in any of these. Dodd et al. 27 (at the APS Meeting in New York, 1967) quote results from a similar search in their 3-BeV/c $K^+p$ experiment for the reactions $K^+p \rightarrow K^+\pi^+n$ and $K^+p \rightarrow \pi^+\pi^+nK^0$. They do not find any indication for
$K^+ p \rightarrow K^+ \pi^- \pi^+ p \ 4.6 \text{ GeV/c}$

2551 events

Fig. 29
$K^+ p \rightarrow K^0 \pi^+ \pi^0 p \quad 4.6 \text{ BeV/c}$

744 events

$a) K^{*0}$

$M(p\pi^+)$ vs $M(K^0\pi^0)$

$b) K^{*+}$

$M(p\pi^0)$ vs $M(K^0\pi^0)$

$c) K^{*+}, K^{*0}, N^{*++}$

$M(K^0p)$ vs $M(\pi^+\pi^0)$

216 events

$d) \text{ Location of } T_0, T_1 \text{ K+p bands}$

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Fig. 30
$K^+ p \rightarrow K^0 \pi^+ \pi^+ \pi^- \pi^0$ 4.6 GeV/\c
165 events

(a) $K^{*+}$

(b) $M(K^0 \pi^+)$ (GeV)

(c) $K^{*+}$ out,
77 events

Location of $T=1$ $KN$ band

Fig. 31
such peaks, either. They quote that with 90% confidence the upper limit for the production cross section in the channel $K^+p \to \pi^+(K^+n)$ is 25 $\mu$b. Similarly, in the channel $K^+p \to \pi^+(K^0\bar{p})$ it is 40 $\mu$b, and in $K^+p \to \pi^+(nK^0\pi^+)$ it is 30 $\mu$b. Their mass distributions are shown in Figs. 32a, b, and c.

Acknowledgement

I wish to acknowledge the important contributions of Roger W. Bland and Benjamin C. Shen to this report.
K⁺p, 3.0 BeV/c; Dodd et al.

(a) K⁺p → K⁺π⁻n
Mass of (K⁺n) combination for all events excluding K⁺n not K⁺π⁻n

(b) K⁺p → π⁺n⁻π⁻π⁺
Mass of (π⁺n⁻π⁻) combination for all events where (K⁺π⁻n) is not K⁺π⁻n

(c) K⁺p → π⁺p⁻K⁺
Mass of (K⁺p) combination excluding π⁺, K⁺n⁻π⁻, for all events excluding K⁺n < 0.9

Fig. 32
References


