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SEARCH FOR X^0 AND φ PRODUCED IN π^+p INTERACTIONS

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September 22, 1965
Search for $X^0$ and $\phi$ Produced in $\pi^+ p$ Interactions†

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September 22, 1965

The investigation of reactions of the form $K^- + p \rightarrow \Lambda^0 + $ resonance has led to the discovery of the $\phi$ (1019 MeV) [1] and $X^0$ (959 MeV) mesons [2].

In film obtained in an exposure of the Brookhaven National Laboratory 20-inch hydrogen bubble chamber to a 3.65-BeV/c $\pi^+$ beam, we have searched for production of both of these particles in reactions of the type

$$\pi^+ + p \rightarrow \pi^+ + p + X^0 \quad (1a)$$

or

$$\pi^+ + p \rightarrow \pi^+ + p + \phi. \quad (1b)$$

It has already been noted by Lee et al. that $\phi$ production in 3.7-BeV/c $\pi^- p$ interactions is very small or nonexistent [3]. However, if the important channel for either of these reactions is

$$\pi + p \rightarrow N^*(1238) + X^0 \quad (2a)$$

or

$$\pi + p \rightarrow N^*(1238) + \phi. \quad (2b)$$

we expect to gain a factor of 9 in their intensity through the use of incident $\pi^+$ mesons.

We find the following: (i) the $X^0$ is indeed produced with a cross section of about 50 $\mu$b and, within our statistics, exclusively via (2a); (ii) in the reactions *This work was done under the auspices of the U. S. Atomic Energy Commission.
\[ \pi^+ + p \rightarrow \pi^+ + p + K + \bar{K}, \]  

an enhancement in the \( K\bar{K} \) invariant mass in the 1000- to 1050-MeV region is indeed observed, in agreement with the result of Abolins et al. [4], but our data do not agree with the interpretation that these events are to be associated with the \( \phi \) meson, as the observed width is far too large.

We first discuss the \( X^0 \) production. The topology investigated is of the type

\[ \pi^+ + p \rightarrow 2\pi^+ + \pi^- + p + \text{MM}, \]  

(3)

where the missing mass carried by the neutral particles is significantly larger than that corresponding to a single neutral pion. The missing-mass distribution for the 492 events having the topology (3) indicates only very weak \( \eta \) production.

We estimate an upper limit of 50 for the number of events in which the missing particle is an \( \eta \), corresponding to a cross section of less than 150 \( \mu \)b for the process \( \pi^+ + p \rightarrow 2\pi^+ + \pi^- + p + \eta \).

We have selected for further study a sample of 142 events by imposing the constraint on (3) that the missing mass equals the mass of the \( \eta \) within the measurement errors. We estimate that less than 40% of these events really involve production of an \( \eta \); those remaining are background events containing two or more neutral pions whose invariant mass lies close to 550 MeV. In our further discussion we deal with the entire sample of 142 events and, for simplicity, refer to the missing particle as an \( \eta \).

In Fig. 1 we show a scatter plot of the \( \pi^+ \pi^- \eta \) invariant mass versus the accompanying \( p\pi^+ \) mass for those events for which either possible value of the \( \pi^+ \pi^- \eta \) mass lies between 830 and 1030 MeV. We find that 18 events satisfy this condition; for three of these events both possible \( \pi^+ \pi^- \eta \) mass combinations are
shown, because both lie in the above-defined range. A clear grouping of eight events in the immediate neighborhood of 960 MeV is observed. In all eight the associated $\rho \pi^+$ mass lies in the $N_{*}^{++}$ band, i.e., between 1140 and 1300 MeV. The weighted-mean $\pi\pi\eta$ mass for these events is $960 \pm 2$ MeV, in good agreement with the value $959 \pm 2$ MeV obtained from the $K^-$ experiments [2, 5]. The three-body phase space corresponding to reaction (1a) predicts that only 20% of the events should lie within the $N_{*}^{++}$ band. The background events outside the 960-MeV cluster agree with this phase-space prediction, thus showing no significant amount of $N_{*}^{++}$ production. It is also worth pointing out that the $N_{*}^+ X^0$ events are produced much more peripherally than the background events in the 830- to 1030-MeV mass region. For all eight $X^0$ events the cosine of the $\rho \pi^+$ production angle in the overall center of mass is less than -0.6, whereas only half of the background events lie in this angular region. Although our sample is small, the $X^0 \rightarrow \pi^+ \pi^- \eta$ decay has such unique characteristics, and the background in the region of $\pi\pi\eta$ mass below 1000 MeV is sufficiently small that we feel very confident in our $X^0$ identification. We have also looked for $X^0$ production in six-prong events of the type $\pi^+ + p \rightarrow p + 3\pi^+ + 2\pi^- + \pi^0$ for which one $\pi^+ \pi^- X^0$ combination has an invariant mass compatible with that of the $\eta$. Of 31 such events we find three which fit reaction (2a), in good agreement with the results from the four-prong events when due account is taken of the branching ratios of the $\eta$ [6]. If we take the branching ratio

$$\frac{X^0 \rightarrow \pi^+ \pi^- (\eta \rightarrow \text{neutrals})}{X^0 \rightarrow \text{all modes}}$$

to be 0.36 [5], the cross section for reaction (2a) is $47^{+20}_{-14}$ $\mu$b.

† Most background events have $\pi^+ \pi^- \eta$ masses above 1050 MeV; hence the identification of $X^0$ decays is unambiguous in spite of the small numbers.
We now consider \( \phi \) production. We have examined events that fit the reactions

\[
\pi^+ + p \rightarrow \pi^+ + p + K^+ + K^-
\]  
(4)

and

\[
\pi^+ + p \rightarrow \pi^+ + p + K^0 + \bar{K}^0.
\]  
(5)

Forty-six events fit reaction (4), with regard to both kinematic fit and ionization, leading to a cross section of \( 0.10 \pm 0.02 \) mb. Twenty-nine events corresponding to (5) have been found, of which six have two \( K_1^0 \rightarrow \pi^+ + \pi^- \) decays, the rest having just one such decay. After correction for decay loss and unseen decays, the total cross section for (5) is \( 0.12 \pm 0.03 \) mb.

The general properties of the \( p\pi^+ \) and \( KK \) mass distributions are shown in the triangle plot of Fig. 2, with appropriate projections onto the \( p\pi^+ \) and \( KK \) axes. The important features are the substantial \( N^{++} \) enhancement, and a marked peak in the \( KK \) mass distribution between threshold and about 1050 MeV, these two effects being completely uncorrelated. Although one may at first sight be tempted to associate the \( KK \) peak with the \( \phi \) meson, this interpretation is not correct. To demonstrate this point we plot in Fig. 3 the \( KK \) mass values and errors in the region below 1050 MeV. It is evident that there is no cluster of masses at any particular value, and especially not at the \( \phi \) mass, 1019.5 MeV [6], which lies within one standard error of only two events.

In order to verify that our estimated mass uncertainties are correct and that there is no significant systematic error in our measurements of effective masses, we have refitted our \( \pi^+ + p \rightarrow \pi^+ + p + K_1^0 + K_1^0 \) events, using the topology \( \pi^+ + p \rightarrow \pi^+ + p + K_1^0 + \pi^+_k + \pi^-_k \), where the \( \pi^+_k \pi^-_k \) pair are the decay products of the second \( K_1^0 \). The invariant mass distribution obtained for the \( \pi^+_k \pi^-_k \) pairs, shown in the inset of Fig. 3, has a mean value of \( 498.5 \pm 1.2 \) MeV, in good agreement with the accepted value of \( 497.7 \pm 0.3 \) MeV [6], and a
width completely consistent with the calculated uncertainties. Further evidence for the validity of our mass determinations is afforded by the fact that our measured value of the $X^0$ mass discussed earlier agrees very well with previous determinations and that the width of the mass distribution is again completely compatible with the calculated errors of measurement. We therefore conclude that our data contain no evidence for $\phi$ production. We set an upper limit of 10 $\mu$b for the total cross section for $\phi$ production in reactions (1b) and (2b).

A comparison of neutral-meson production in reactions of the form $K^- + p \rightarrow \Lambda^0 + M^0$ and $\pi^+ + p \rightarrow N^{*++} + M^0$, where $M^0$ is a neutral meson, is given in Table I. The $K^-$ results are taken from data at center-of-mass energies as close as are available to the one in the present experiment. It is interesting to note that, whereas in $\pi^0, X^0, \eta$, and $\omega$ production the $\pi^+$ and $K^-$ channels have comparable effectiveness, $\phi$ production by the pion channel is strongly suppressed. If we assume that the principal mechanism for $\omega$ production is $\rho$ exchange [7], then the low $\phi$ production in $\pi^+ p$ interactions is presumably related to the very small $\phi \rho \pi$ coupling, another manifestation of which is the low rate of the decay $\phi \rightarrow \rho + \pi$ [8]. It is also interesting to note the very marked difference between the $K^-$ and $\pi^+$ cross sections for $\rho$ production.

Given that the observed $K\bar{K}$ enhancement is not due to $\phi$ production, it is presumably the same effect as one of the $K\bar{K}$ enhancements near threshold that have already been reported [10-12]. Evidence for an $I=0, S$-wave $K\bar{K}$ interaction has been reported by Alexander et al. [10], and Armenteros et al. have observed a possible $I=1, K\bar{K}$ interaction [11]. Recently Miller et al. have reported a new $K\bar{K}\pi$ resonance at 1280 MeV whose decay angular and
energy distributions are somewhat suggestive of the existence of an \( I = 1 \), \( S \)-wave \( K\bar{K} \) interaction [12]. The only contribution we can make from our very limited sample is to note that for an isoscalar \( K\bar{K} \) state, pion exchange might be expected to play an important role leading to considerable simultaneous \( N^{*++} \) production, in contradiction to the experimental observations. On the other hand, an \( S \)-wave isovector \( K\bar{K} \) enhancement having the quantum numbers \( I^G J^P = 1^{-0^+} \) cannot be produced by \( \pi \), \( \rho \), or \( \omega \) exchange, and would therefore not necessarily be associated with \( N^{*++} \). Obviously, considerably more data are required to establish this interpretation.

We wish to express our appreciation to Ralph Shutt for making the Brookhaven 20-inch bubble chamber available to us, Hugh Brown for help with the run at Brookhaven, the AGS and 20-in. bubble-chamber crews, and our scanning, measuring, and computing staffs. We also wish to acknowledge the help of Benjamin C. Shen in various stages of this work.
Table I. Comparison between cross sections for the production of neutral nonstrange mesons ($M^0$) in the reactions $K^- + p \rightarrow \Lambda^0 + M^0$ and $\pi^+ + p \rightarrow N^{*++} + M^0$. All $\pi^+ p$ results except the $\pi^0$ production are from this experiment.

<table>
<thead>
<tr>
<th>Meson</th>
<th>$K^- + p \rightarrow \Lambda^0 + M^0$</th>
<th>$\pi^+ + p \rightarrow N^{*++} + M^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>K Momentum (BeV/c)</td>
<td>Cross section (µb)</td>
</tr>
<tr>
<td>$\pi^0$</td>
<td>3.0</td>
<td>138 ± 15 a)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\eta$</td>
<td>2.45</td>
<td>50 ± 15 d)</td>
</tr>
<tr>
<td>$\rho^0$</td>
<td>2.45</td>
<td>150 ± 24 d)</td>
</tr>
<tr>
<td>$\omega$</td>
<td>2.45</td>
<td>320 ± 70 d)</td>
</tr>
<tr>
<td>$\chi^0$</td>
<td>3.0</td>
<td>77 ± 15 f)</td>
</tr>
<tr>
<td>$\phi$</td>
<td>3.0</td>
<td>38 ± 7 f)</td>
</tr>
<tr>
<td>$f^0$</td>
<td>3.65</td>
<td>130 ± 50</td>
</tr>
</tbody>
</table>

a) Reference 13
b) Reference 14
c) Reference 15
d) Reference 16. The $\Lambda^0 \omega$ and $\Lambda \eta$ cross sections are based on the fractions, 16% and 0.8%, of the reaction $K^- + p \rightarrow \Lambda^0 + \pi^+ + \pi^- + \pi^0$ going into $\eta$ and $\omega$ production, corrected by the appropriate branching ratios. Both these fractions are based on more complete data than those in the UCRL report, and the errors quoted reflect to some extent the fact that the analysis is not yet complete and are therefore larger than the statistical uncertainties. We are indebted to Stanley Flatté, Lawrence Radiation Laboratory, for giving us these results.
e) Based on observation of the $\pi^+ \pi^- \pi^0$ mode corrected by the appropriate branching ratio.
f) Reference 9. The quoted $\phi$ cross section contains only the contributions from the $K^+K^-$ and $K^0\bar{K}^0$ decay modes.
References


7. B. E. Y. Svensson, Nuovo Cimento 37 (1965) 714, has shown that the experimental data on the reaction $\pi^+ + p \rightarrow \omega + N^{*+}$ are in reasonably good accord with the expectations from $\rho$ exchange modified by absorption effects.

8. J. S. Lindsey and G. A. Smith, Phys. Rev. Letters 15 (1965) 221, give a branching ratio $(\phi \rightarrow \rho \pi)/(\phi \rightarrow \text{all modes})$ of $18 \pm 8\%$. On the other hand, a ratio of $51 \pm 9\%$ has been found by Badier et al. (reference 9).


FIGURE CAPTIONS

Fig. 1. Scatter plot of $p\pi^+$ mass versus $\pi^+\pi^-\eta$ mass for all events for which the $\pi^+\pi^-\eta$ mass lies between 830 and 1030 MeV. Three events are plotted twice, having both $\pi^+\pi^-\eta$ combinations in the required range.

Fig. 2. Triangle plot of $p\pi^+$ mass versus $K\bar{K}$ mass, with both projections shown.

Fig. 3. Scatter plot of $p\pi^+$ mass versus $K\bar{K}$ mass for all events for which the $K\bar{K}$ mass is less than 1050 MeV. For the topology $\pi^+ + p \rightarrow \pi^+ + p + K^0 + \bar{K}^0$, only events with a single $K^{\prime\prime}_1 \rightarrow \pi^+ + \pi^-$ decay are shown. The inset shows the $\pi^+\pi^-$ invariant mass distribution from $K^{\prime\prime}_1$ decays in events of the type $\pi^+ + p \rightarrow \pi^+ + p + K^0_1 + K^0_1$ fitted as $\pi^+ + p \rightarrow \pi^+ + p + K^0_1 + (\pi^+ + \pi^-)$. 
Fig. 1
\[ p\pi^+K^+K^- + p\pi^+K^0K^0 \rightarrow p\pi^+(\pi^+\pi^-)K^0 \]
\[ \Theta p\pi^+K^0K^0 \rightarrow p\pi^+(\pi^+\pi^-)(\pi^+\pi^-) \]

![Diagram](image)

Fig. 2
Fig. 3
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