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OMEGA PRODUCTION IN $pp \rightarrow pp \pi^+ \pi^- \pi^0$ AT 6.6 GeV/c

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October 1969

ABSTRACT

We present a study of the $3\pi$ system in $pp \rightarrow pp \pi^+ \pi^- \pi^0$ at 6.6 GeV/c. Both $\eta(549)$ and $\omega(783)$ production are observed. The Dalitz plot is displayed for the $pp\omega$ events, in addition to several other experimental distributions. There is no evidence for $p\omega$ resonances. The $pp\omega$ events have been assigned separately to the six possible multiperipheral diagrams on the basis of criteria in the four-momentum transfers and c.m. longitudinal momenta, respectively. In addition we discuss the means of achieving an effective diagram separation.

I. INTRODUCTION

We have analyzed 6098 events of the type

$$p + p \rightarrow p + p + \pi^+ + \pi^- + \pi^0$$

at a laboratory momentum of 6.6 GeV/c. The data were obtained in the Lawrence Radiation Laboratory's 72-inch liquid-hydrogen bubble chamber. The experimental details can be found elsewhere.\textsuperscript{1,2} The cross section for reaction (1) is found to be $2.15 \pm 0.13$ mb at 6.6 GeV/c. Reaction (1) is dominated by $\Delta(1238)$ production\textsuperscript{3} and, to a lesser extent, by vector-meson production. Vector-meson production has been reported in proton-proton collisions for beam momenta between 4 and 10 GeV/c.\textsuperscript{4-10}
In this work we present a study of $\omega(783)$ production. Since little data on $\omega$ production in proton-proton interactions has been reported in the intermediate-energy range, we present the data with the hope that they will supply some understanding of the production mechanisms responsible for the $pp\omega$ intermediate state.

In Section II we discuss the $3\pi$ system and the vector-meson production in reaction (1). In Section III we present our conclusions.

II. DISCUSSION

The spectrum of $3\pi$ effective mass for the 6098 examples of reaction (1) is displayed in Fig. 1. Both $\eta(549)$ and $\omega(783)$ meson production are observed. We have performed a fit of the $M^2(\pi^+\pi^-\pi^0)$ spectrum to Gaussians for the $\eta$ and $\omega$ resonances, plus a slowly varying background, in order to determine the respective cross sections. The cross sections for $pp\eta$ and $pp\omega$ are presented in Table I along with those values determined from other experiments.<sup>4-10</sup> The tabulated results refer only to the $pp\pi^+\pi^-\pi^0$ final state. Above 5 GeV/c the $pp\eta$ and $pp\omega$ cross sections appear relatively constant if the different methods of determination are considered.

The $3\pi$ mass spectra for events occurring in the three denoted regions of $3\pi$ c.m. longitudinal momenta are given in Figs. 2(a-c). Figures 2(a-c) indicate that the $\omega$ signal/noise ratio increases with the magnitude of the $3\pi$ c.m. longitudinal momenta. Another enhancement is present in Fig. 2(b) in the region of 1000 MeV. We estimate by eye that no more than 100 events or 35 $\mu$b is represented in this enhance-
ment. However, the maximum cross section to be expected for $\Phi(1019)$ production in this final state is no more than 3 or 4 $\mu$b so the major part of this effect must be due to other causes.

The high background present under all of the peaks occurring in Figs. 1 and 2 precludes any further analysis of the smaller effects, so we restrict ourselves henceforth to a study of $\omega$ production in the reaction.

$$p + p \rightarrow p + p + \omega$$

We define the $\omega$ events to be those 671 events with $0.76 < M(\pi^+ \pi^- \pi^0) < 0.82$ GeV. The non-$\omega$ background in this mass slice is roughly 40% and does contain $\Delta^{++}\pi^- \pi^0$ events. The $pp\omega$ Dalitz plot is presented in Fig. 3. The Dalitz plot is not uniformly populated: the points tend to cluster along the boundaries of low $M^2(\omega\pi)$. The projection of $p\omega$ mass is given in Fig. 4. Two combinations are plotted for each event. There does not appear to be any significant evidence for resonances in the $p\omega$ system. The single particle four-momentum transfer distributions for the $pp\omega$ events are given in Fig. 5. Figure 5(a) is the distribution of the lower of the two possible values of $t$ (we define $t$ to be positive in the physical region) from the beam or target proton to an outgoing proton. Two combinations are plotted for each event. This distribution peaks at low values of $t$. Figure 5(b) is the distribution of $t$ from the beam proton to the $\omega$. Although Fig. 5(b) does peak at low values of $t$ it is not exemplary of a very peripheral $t$ distribution.
The peripheral nature of the ppω data at 6.6 GeV/c and the apparent absence of resonances in the ω system, in addition to the character of the ppω Dalitz plot, suggest that ω production is proceeding via some multiperipheral process [see Fig. 6(a)]. We would expect the dominant process to involve production of peripheral protons at each outer vertex of Fig. 6(a). Figure 7 displays a t₁ vs t₂ scatter plot where t₁ is the lower of the two possible momentum transfers from the beam or target proton to the ith outgoing proton. The multiperipheral nature of some of the ppω events is clearly seen in Fig. 7 in the region of simultaneously small values of t₁ and t₂.

The six multiperipheral processes that can occur for pp → ppω are shown in Fig. 6(b): they are denoted by Roman numerals I to VI inclusive. Diagrams I and V are restricted to meson exchange, while the processes II, III, IV, and VI require both baryon and meson exchange. One difficulty with a multiperipheral analysis is the assignment of physical events to the correct diagram. The two current methods of diagram separation are the |t_a + t_b| minimum¹⁴ and the P_L3 > P_L4 > P_L5 criteria,¹⁵ where t_a = -(P_1 - P_3)^2 and t_b = -(P_2 - P_5)^2 in the language of Fig. 6(a). The c.m. longitudinal momentum of the ith particle is denoted by P_Li. The results of the two methods of diagram separation as applied to the 671 ppω events are given in Table II for diagrams I through VI. The two different separation procedures yield results consistent with each other. The two diagrams representing only meson exchange (I,V) apparently account for 50-60% of the data.¹⁶
The interference between two amplitudes generally diminishes as one amplitude becomes weaker in comparison with the other. In Tables III [(A) and (B)] we attempt to indicate the magnitude of the interferences between different amplitudes (i.e., diagrams) as a function of the momentum transfers at the external vertices of Fig. 6(a) \( (t_a \text{ and } t_b) \). Specifically, the events in Tables III[(A) and (B)] were assigned to the six processes by the \( |t_a + t_b| \) minimum and \( P_{L3} > P_{L4} > P_{L5} \) criteria, respectively. In addition, the numbers within the parentheses represent those events that had simultaneous momentum transfers \( t_a \) and \( t_b \), corresponding to the accompanying processes (also in parenthesis), less than the maximum denoted value. For example, in Table III(A), of the 93 events assigned to diagram I with \( t_a \) and \( t_b \) both less than 0.5 GeV\(^2\), seven events simultaneously had other \( t_a, t_b \) combinations corresponding to diagrams II and III, both less than 0.5 GeV\(^2\). The overlapping events can be interpreted as an indication of possible interferences between processes I, II, and III to the tune of roughly 10% when \( t < 0.5 \text{ GeV}^2 \). As we take events with higher and higher \( t \) values the interference or overlap becomes larger. From Tables III it appears that with enough events one could proceed with a noninterference analysis of \( \omega \) production by simultaneously requiring \( t_a \) and \( t_b \) to be less than 0.5 GeV\(^2\).

III. CONCLUSIONS

At 6.6 GeV/c the cross section for \( \omega \) meson production in the reaction \( pp \to pp \pi^+\pi^-\pi^0 \) is \( 180 \pm 23 \text{ \mu b} \). The \( \omega \) production systematically accounts for 6-10% of the cross section of the \( pp3\pi \) reaction from
In the $\pi^+\pi^-\pi^0$ mass spectrum the $\omega$ signal/noise ratio increases with the magnitude of the $3\pi$ c.m. longitudinal momentum. We have studied the reaction $pp \rightarrow ppm$ by just considering the 671 events in the $3\pi$ mass region of 0.76 - 0.82 GeV. The non-$\omega$ background in this mass slice is roughly 40% and does contain $\Delta^{++}\pi^+\pi^-\pi^0$ events. The $\rho\omega$ mass spectrum is peaked at low values and shows no evidence for $\rho\omega$ resonances.

The momentum transfer distributions of both protons and $\omega$'s are peaked at low values. In addition, many of the events are multiperipheral. As a first approximation at separation the 671 $pp\omega$ events were assigned to the six possible multiperipheral diagrams on the basis of the $|t_a + t_b|$ minimum and $P_{L3} > P_{L4} > P_{L5}$ criteria. The two diagrams requiring only meson exchange in both legs account for 50-60% of the $pp\omega$ events. However, an effective separation of diagrams with overlaps less than 10% of the time requires the momentum transfers in each leg to be simultaneously less than 0.5 GeV$^2$.

ACKNOWLEDGMENTS

We thank Gerald A. Smith and Peter E. Schlein for help and discussions in the early stages of the experiment.
FOOTNOTES AND REFERENCES

* Work supported by the U. S. Atomic Energy Commission.


11. A. B. Wicklund, private communication. At 6.6 GeV/c the cross section for $pp \to pp\phi(1019), \phi \to \Sigma^+$ is no more than 5 mb. In addition, the branching ratio $(\phi \to \Sigma^+ K^0) / (\phi \to 3\pi^-)$ is greater than 1 (see Lawrence Radiation Laboratory Report UCRL-8030-Rev.).

12. J. C. Berlinghieri, M. S. Farber, T. Ferbel, R. Holmes, P. F. Slattery, S. Stone, and H. Yuta, Phys. Rev. Letters 23, 42 (1969). An excess of events in the $\pi^+\pi^-\gamma$ mass spectrum in the region of 1000 MeV for the reaction $K^+p \to K^+\pi^+\pi^-\gamma$ at 12.7 GeV/c is also detected. The authors interpret the excess to be due to $A_1$ production. However, in our case, no $\rho(765)$ production is observed. Perhaps the excess is due to $\eta'(960)$ production which may occur in the misidentified events $pp \to pp\pi^+\pi^-\gamma$.

13. We find that $\Delta^{++}(1238)$ production accounts for approximately 60% of the $pp\pi^+\pi^-\gamma$ final state.

14. G. Alexander, A. Firestone, C. Fu, G. Goldhaber, and A. Pignotti, Phys. Rev. 177, 2092 (1969). They attempt to fit the data for $K^+p \to K^+\pi^+\gamma$ at 9 GeV/c by a double Regge pole model calculation. Diagram separation procedures are discussed.


16. The reader should bear in mind that this percentage is only a first approximation. Detailed fits of the $pp\phi$ data to specific multi-
peripheral models (e.g., Regge model) are necessary to ascertain the actual percentage of the data assigned to each diagram.
Table I. Experimental cross sections for resonance production in $pp \to pp \pi^+ \pi^- \pi^0$ (in $\mu b$).

<table>
<thead>
<tr>
<th>Beam Momentum (GeV/c)</th>
<th>4.4</th>
<th>4.95^5</th>
<th>5.52^6</th>
<th>6^7</th>
<th>6^8</th>
<th>6.6</th>
<th>6.92^9</th>
<th>10^10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
<td>$pp \to pp\eta$</td>
<td>$pp \to pp\omega$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>40±20</td>
<td>28±9</td>
<td>20±10</td>
<td>70±50</td>
<td>28±5</td>
<td>29±9</td>
<td>40±10</td>
<td>36±15</td>
</tr>
<tr>
<td></td>
<td>80±30</td>
<td>152±18</td>
<td>110±20</td>
<td>180±50</td>
<td>104±12</td>
<td>180±23</td>
<td>140±40</td>
<td>145±30</td>
</tr>
</tbody>
</table>

Table II. Number of events assigned to each diagram illustrated in Fig. 6(b) for the 671 $pp \to pp\omega$ events at 6.6 GeV/c.

<table>
<thead>
<tr>
<th>Diagram</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>t_a+t_b</td>
<td>_{\text{minimum}}$</td>
<td>200</td>
<td>77</td>
<td>88</td>
<td>89</td>
</tr>
<tr>
<td>$P_{L5} &gt; P_{L4} &gt; P_{L5}$</td>
<td>221</td>
<td>68</td>
<td>79</td>
<td>65</td>
<td>182</td>
<td>56</td>
</tr>
</tbody>
</table>
Table III. Number of events assigned to each diagram [illustrated in Fig. 6(b)] with $t_a, t_b$ both less than the maximum value listed in column 1. The numbers in parenthesis represent those events that also have $t_a, t_b$ combinations, corresponding to the processes (also in parenthesis), both less than the same maximum value.

(A) Diagram separation by $|t_a + t_b|$ minimum criteria.

<table>
<thead>
<tr>
<th>Maximum $t_{a,b}$ value (GeV$^2$)</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>33(0)</td>
<td>16(0)</td>
<td>16(0)</td>
<td>11(0)</td>
<td>23(0)</td>
<td>9(0)</td>
</tr>
<tr>
<td>0.5</td>
<td>93(7,II,III)</td>
<td>33(4,I)</td>
<td>35(4,I)</td>
<td>41(4,V)</td>
<td>68(8,IV,VI)</td>
<td>25(2,V)</td>
</tr>
<tr>
<td>0.7</td>
<td>126(24,II,III)</td>
<td>48(13,I)</td>
<td>47(10,I)</td>
<td>48(12,V)</td>
<td>93(26,IV,VI)</td>
<td>39(7,V)</td>
</tr>
<tr>
<td>1.0</td>
<td>154(74,II,III)</td>
<td>54(24,I)</td>
<td>69(28,I)</td>
<td>58(28,V)</td>
<td>125(52,IV,VI)</td>
<td>45(22,V)</td>
</tr>
</tbody>
</table>

(B) Diagram separation by $P_{L2} > P_{L4} > P_{L5}$ criteria.

<table>
<thead>
<tr>
<th>Maximum $t_{a,b}$ value (GeV$^2$)</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>33(0)</td>
<td>16(0)</td>
<td>16(0)</td>
<td>11(0)</td>
<td>23(0)</td>
<td>9(0)</td>
</tr>
<tr>
<td>0.5</td>
<td>97(13,II,III)</td>
<td>29(2,I)</td>
<td>32(0)</td>
<td>32(0)</td>
<td>74(21,IV,VI)</td>
<td>21(0)</td>
</tr>
<tr>
<td>0.7</td>
<td>132(39,II,III)</td>
<td>39(10,I)</td>
<td>41(7,I)</td>
<td>37(7,V)</td>
<td>101(43,IV,VI)</td>
<td>33(4,V)</td>
</tr>
<tr>
<td>1.0</td>
<td>164(91,II,III)</td>
<td>44(18,I)</td>
<td>62(24,I)</td>
<td>44(18,V)</td>
<td>141(73,IV,VI)</td>
<td>38(16,V)</td>
</tr>
</tbody>
</table>
FIGURE CAPTIONS

Fig. 1. $\pi^+\pi^-\pi^0$ invariant mass for the 6098 pp $\rightarrow$ pp $\pi^+\pi^-\pi^0$ events at 6.6 GeV/c.

Fig. 2. $\pi^+\pi^-\pi^0$ invariant mass subject to selection on the $3\pi$ c.m. longitudinal momentum:
   (a) $P_L < 0.3$ GeV/c
   (b) $0.3 < P_L < 0.6$ GeV/c
   (c) $P_L > 0.6$ GeV/c.

Fig. 3. $\pi\pi\omega$ Dalitz plot for the 671 events with $0.76 < M(\pi^+\pi^-\pi^0) < 0.82$ GeV.

Fig. 4. The $\pi\omega$ invariant mass for the 671 pp $\rightarrow$ pp$\omega$ events at 6.6 GeV/c.
   Two combinations are plotted for each event.

Fig. 5. Four-momentum transfer distributions for the 671 pp $\rightarrow$ pp$\omega$ events at 6.6 GeV/c:
   (a) The lower of the two possible values of $t$ from the beam or target proton to an outgoing proton. Two combinations are plotted for each event.
   (b) $t$ from the beam proton to the $\omega$.

Fig. 6. (a) Double peripheral diagram. (b) The six possible multiperipheral diagrams for the reaction pp $\rightarrow$ pp$\omega$.

Fig. 7. $t_1$ vs $t_2$ scatter plot for the 671 pp $\rightarrow$ pp$\omega$ events at 6.6 GeV/c.
   $t_1$ is the lower of the two possible momentum transfers from the beam or target proton to the 1. outgoing proton.
pp \rightarrow pp \pi^+\pi^-\pi^0

6098 events
6.6 GeV/c
Fig. 2.
Fig. 3.

$pp \rightarrow pp\omega$ 6.6 GeV/c

671 events
Fig. 4.
(a)

1  a  3
   b
2  4
   5

(b)  

I  
\[ p_b \]  \[ p_1 \]  \[ p_2 \]  \[ \omega \]  
\[ p_t \]  

IV  
\[ p_b \]  \[ \omega \]  
\[ p_2 \]  
\[ p_1 \]  

II  
\[ p_b \]  \[ p_1 \]  \[ p_2 \]  \[ \omega \]  
\[ p_t \]  

V  
\[ p_b \]  \[ \omega \]  
\[ p_2 \]  
\[ p_1 \]  

III  
\[ p_b \]  \[ \omega \]  
\[ p_1 \]  
\[ p_2 \]  

VI  
\[ p_b \]  \[ p_2 \]  
\[ p_1 \]  
\[ \omega \]  

Fig. 6.
Fig. 5.
$pp \rightarrow pp\omega$ 6.6 GeV/c

671 events

$t_1$ (GeV$^2$)

t_2$ (GeV$^2$)

XBL 6910 - 6036

Fig. 7.
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