Diffractive Pion Dissociation into $\pi^-\pi^+\pi^-\pi^+$ at COMPASS

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Abstract. At the COMPASS experiment a sample of $\sim 380000$ exclusive events of diffractive pion dissociation on a lead target into a $\pi^-\pi^+\pi^-\pi^+$ final state has been recorded in 2004. The 5$\pi$ invariant mass spectrum shows a momentum transfer dependent structure peaking around 1.8$\text{GeV}/c^2$. In the $(4\pi)^0$ subsystem there is a clear signal for the $f_1(1285)$ resonance decaying into 4 pions. In this note we describe the data sample and explore the physics potential of this final state.

Keywords: exotic mesons, partial wave analysis, diffraction

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INTRODUCTION

In 2004 the COMPASS experiment conducted its first pilot run dedicated to the physics of meson spectroscopy. During a few days of data taking events from a 190$\text{GeV}/c$ pion beam impinging on a lead target have been recorded. A general overview of the COMPASS spectrometer can be found in [1]; a detailed description is available in [2]. The first process that has been studied in detail using the 2004 data was diffractive dissociation into three charged pions [3]. A partial wave analysis of this final state yields a significant signal in the spin exotic $J^{PC}=1^{-+}$ partial wave. In this note we describe the data set that is available if two more charged pions are required in the final state. Thus the reaction under investigation reads:

$$\pi^- + \text{Pb} \to \pi^- \pi^+ \pi^- \pi^+ X$$

where $X$ stands for the recoil system which is unobserved in the 2004 setup of COMPASS. As more particles are created in the reaction, the total invariant mass of the 5$\pi$ system tends to be higher than in the 3$\pi$ case, which makes resonances above 2$\text{GeV}/c^2$ accessible. Moreover the system allows for a variety of intermediate resonant states to be present either in the 4$\pi$ or 3$\pi$ subsystem so that possibly interesting, complex decay modes can be explored. The flux-tube model for mesons [4] makes detailed predictions [5] on such multi-particle decay modes. Of special interest in this context are the predictions for the decay of a $J^{PC}=1^{-+}$ hybrid meson [6, 7].

<table>
<thead>
<tr>
<th>$m_\pi$</th>
<th>$b_1\pi$</th>
<th>$f_1\pi$</th>
<th>$\eta'\pi$</th>
<th>$\rho(1450)\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6$\text{GeV}$</td>
<td>24 :</td>
<td>5 :</td>
<td>2 :</td>
<td></td>
</tr>
<tr>
<td>2.0$\text{GeV}$</td>
<td>43 :</td>
<td>10 :</td>
<td>27 :</td>
<td>12 :</td>
</tr>
</tbody>
</table>

Table 1 shows flux-tube model calculations for the branching fractions of the $J^{PC}=1^{-+}$ hybrid meson [7]. A distinct feature of these calculations is the $b_1\pi$ to $f_1\pi$ partial width ratio which also is in very good agreement with studies on the lattice [8]:

$$\frac{\Gamma(\pi^- \to b_1\pi)}{\Gamma(\pi^- \to f_1\pi)} = 4$$

(1)

All of the isobars in Table 1 are allowed to decay to 4 charged pions. The $f_1(1285)$ and the $\rho(1450)$ have been seen in $\pi^-\pi^+\pi^-\pi^-$ decays. While the charged $b_1(1235)$ with isospin $I = 1$ and $I_z = \pm 1$ is dominantly decaying through $\omega\pi$ there is no obvious reason why the $I_z = 0$ state should not decay into 4 charged pions. Also the heavy $\eta(1405)$ is reported in this channel. This means they all can be expected to contribute to the 5$\pi$ final state. A similar study in a different final state has been carried out at BNL [9]. They have analyzed the $f_1(1285)\pi$ system in the decay channel $f_1(1285) \to \omega\pi$ and indeed they find a contribution of the spin-exotic $1^{-+}$ wave.
Another open issue is the nature of the $J^{PC} = 1^{++}$ wave which is known to have some structure around 1.7 GeV/$c^2$. Yet it is unclear so far, whether there is a single $a_1(1700)$ state or whether one can confirm the indications that there might actually be several states with these quantum numbers in the mass range from 1.6 to 2 GeV/$c^2$ (for a review on these issues see [10] and references therein). In the pseudoscalar sector the $\pi(1800)$ resonance is a well-known object. Its decay pattern however is far from being understood [10]. From a study of the $\eta \eta \pi^-$ final state the VES collaboration has reported a decay of the $\pi(1800)$ into $f_2(1500)\pi$ [11]. This result has been confirmed by E852 [12] in the same final state. The $5\pi$ data will be used to verify these results in a high-multiplicity final state. Furthermore in the $J^{PC} = 2^{++}$ quantum numbers a controversy over the existence of a non-exotic hybrid meson $\pi_2(1880)$ is ongoing. Several states have been reported in the range from 1.6 to 2.2 GeV/$c^2$ yet the situation remains unclear [10].

For all these investigations the potential wealth of different possible decay modes contained in the $5\pi$ final state holds great promise although challenges of an unambiguous analysis have to be overcome.

**THE $\pi^-\pi^+\pi^-\pi^+\pi^-$ DATA SAMPLE**

In the 2004 setup of the COMPASS experiment no recoil detector was present. Thus in order to extract exclusive diffractive dissociation events from the data we require a vertex inside the target with the incoming beam track and 5 outgoing tracks of total charge $q = -1$ and the $5\pi$ system to carry the full beam energy. The exclusivity peak at the nominal beam energy of $E = 189$ GeV can be seen in Figure 1(a). There is a considerable tail of non-exclusive background events which presumably originates from events where one or more particles have not been reconstructed or where a $\pi^0$ is missing. Cutting on the $5\pi$ energy around the quasi-elastic peak $E_{5\pi} \in [189 - 6; 189 + 6]$ GeV yields a sample of 384235 events.

![Energy of 5π System (GeV)](image1)

**FIGURE 1.** Exclusivity and momentum transfer distributions.

Figure 1(b) shows the distribution of the effective squared four-momentum transfer $t'$ for this exclusive event sample. This variable corresponds to the squared four-momentum transfer, corrected for the minimum longitudinal momentum transfer effect. For the further investigations we define three broad bins in this variable as given in Table 2

<table>
<thead>
<tr>
<th>Momentum transfer ranges.</th>
<th>Low-$t'$: $t' \in [0, 0.005]$ GeV$/c^2$</th>
<th>202578 events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium-$t'$: $t' \in (0.005, 0.1]$ GeV$/c^2$</td>
<td>121885 events</td>
<td></td>
</tr>
<tr>
<td>High-$t'$: $t' \in (0.1, 2]$ GeV$/c^2$</td>
<td>58672 events</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2(a) shows the invariant mass spectra for the $5\pi$ final state systems in the different momentum transfer bins. There is a distinct structure visible around 1.8 GeV/$c^2$. In this region we expect the well-known $\pi(1800)$ and $\pi_2(1670)$ resonances. Also the heavy $a_1(1700)$ should show up in this mass range. A comparison of the peaking structure at 1.8 GeV/$c^2$ shows a clear $t'$-dependence. While at low-$t'$ the peak is quite prominent it tends to decrease in intensity (with respect to the higher mass part of the spectrum) for higher momentum transfer.

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The respective exclusivity peaks for the three $t'$-ranges are shown in Figure 2(b). Here it becomes obvious that the background tail which extends to lower total energies is prominent in high-$t'$ and even medium-$t'$ while it is much smaller for the low-$t'$ sample. Future analysis will therefore focus mainly on the low-$t'$ region.

In order to get a first understanding of the possible decay channels through which the $5\pi$ final state is reached we look at the $\pi^+\pi^-\pi^+\pi^-$, the $\pi^-\pi^+\pi^-$ and the $\pi^-\pi^+$ subsystems.

Figure 3 shows the mass spectrum of the neutral $4\pi$ subsystem. The plot exhibits two striking features: The distribution peaks at about 1.4 GeV/$c^2$ extending well above 2 GeV/$c^2$. Even though there is considerable combinatorial background, the spectrum indicates the presence of intermediate isobar resonances of high masses which will have to be taken into account in the partial wave analysis. Furthermore there is a sharp peak at about 1.3 GeV/$c^2$. In order to investigate this further we choose a two-dimensional representation where we plot the mass of a neutral $\pi^+\pi^-$ subsystem out of the $4\pi$ against the $4\pi$ mass in Figure 4(a). Since there are 4 ways to select a neutral $2\pi$ system out of $\pi^+\pi^-\pi^+\pi^-$ there are in total 12 entries per event in this plot.

The peak at 1.3 GeV/$c^2$ in the four-pion mass clearly appears as a sharp band. Also at 1.45 GeV/$c^2$ there is a band structure which, however, is considerably broader. In order to get rid of the strong contributions of the spectrum which cluster around the $p(770)$ band in the $2\pi$ mass we select only those $\pi^+\pi^-\pi^-\pi^+$ combinations where the respective $2\pi$ masses are in the interval $0.28\text{GeV}/c^2 < m(2\pi) < 0.55\text{GeV}/c^2$. The resulting $4\pi$ spectra (for different $t'$-bins) are shown in Figure 4(b) where the 1.3 GeV/$c^2$ peak clearly stands out which we identify as the $f_1(1285)$. 

FIGURE 2. Invariant mass and exclusivity for different squared momentum transfer regions.

FIGURE 3. Invariant mass spectrum of the neutral $4\pi$ subsystem. There are three entries per event in this plot.
FIGURE 4. The \( f_1(1285) \) signal in the \( 4\pi \) subsystem.

In addition to the \( X \rightarrow R^0 + \pi^- \) isobar decay where the isobar \( R^0 \) decays into four pions there is the possibility to have a decay like this:

\[
X \rightarrow R_1 + R_2 \rightarrow (3\pi)^- + (2\pi)^0
\]  

The invariant mass distribution of the negative three-pion subsystems is plotted in Figure 5(a). There are six possibilities to construct such a subsystem out of \( \pi^- \pi^+ \pi^- \pi^- \). The spectrum peaks at 1.1 GeV/c\(^2\) with a shoulder at 1.3 GeV/c\(^2\). Expected resonant contributions to this spectrum are the \( a_1(1260) \), \( a_2(1320) \) and the \( \pi_2(1670) \).

FIGURE 5. \( 3\pi \) and \( 2\pi \) subsystems.

The neutral \( 2\pi \) subsystem is shown in Figure 5(b). Despite considerable combinatorial background the \( \rho(770) \) peak is clearly visible. Also the wide \( \sigma(600) \) contributes to this spectrum while the \( f_0(980) \) and the \( f_2(1270) \) are only faint bumps in the distribution.

MONTE CARLO ACCEPTANCE STUDIES

In order to take into account the acceptance effects of the spectrometer in the partial wave analysis a Monte Carlo simulation of the COMPASS apparatus is used. As a result the average total acceptance is determined to range from
25 to 40% depending on the $5\pi$ mass. Figure 6 shows the angular distributions of accepted Monte Carlo events in the Gottfried-Jackson angle $\theta_{GJ}$, the angle between the beam-axis and a single $\pi^-$ in the rest frame of the decaying $5\pi$ resonance. Six different mass bins are shown which cover the interesting mass range from 1 to 3 GeV/c$^2$. For all mass bins the complete phase space is covered. It becomes apparent that acceptance corrections become important for higher masses.

![Angular Acceptance](image)

**FIGURE 6.** Angular acceptance for high-$t'$ events ($0.1\text{GeV}^2/c^2 < t' < 2\text{GeV}^2/c^2$) as determined by phase space Monte Carlo simulation in different mass bins between 1 and 3 GeV/c$^2$. There are 3 entries per event in each plot.

**CONCLUSIONS**

380000 exclusive $\pi^-\pi^+\pi^-\pi^+\pi^-$ events from diffractive pion dissociation on lead have been recorded by the COMPASS experiment in 2004. The $f_1(1285)$ is clearly visible in the neutral 4$\pi$ invariant mass spectrum. In 2008/09 more data have been taken with a pion beam impinging on a liquid hydrogen target. This data set is also being prepared for detailed analysis (see [13]). The excellent acceptance for charged tracks of the COMPASS spectrometer will open the possibility to perform a partial wave analysis of this final state in the isobar model.

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**REFERENCES**

1. S. Paul, see these proceedings
13. J. Bernhard, see these proceedings