Study of the $D^0 \rightarrow \pi^+ \pi^- \pi^0$ decay at BABAR

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Abstract. The Dalitz-plot of the decay $D^0 \rightarrow \pi^+ \pi^- \pi^0$ measured by the BABAR collaboration shows the structure of a final state having quantum numbers $I^GJ^{PC} = 0^+0^-$. An isospin analysis of this Dalitz-plot finds that the fraction of the $I = 0$ contribution is about 96%. This high $I = 0$ contribution is unexpected because the weak interaction violates the isospin.

Keywords: Charm mesons, D decay, Isospin zero dominance, Tetraquarks


INTRODUCTION

This communication reports the results of the analysis of the Cabibbo suppressed decay

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

made by the BABAR collaboration.

The BABAR detector [1] measured the $e^+e^-$ annihilations at the PEP-II collider. Most of the data were taken at the $\Upsilon(4S)$ resonance to study the $B$ mesons. The detector measured also the decays of the charm mesons and baryons generated by the decay of the $B$ mesons or by the continuum, i.e. by the $e^+e^-$ annihilations into $q\bar{q}$.

The charged tracks were measured by a silicon vertex tracker and by a drift chamber, and identified by a ring-imaging Cherenkov detector. The photons were measured by an electromagnetic calorimeter made of CSI(Tl) crystals. The magnetic field of 1.5 T was generated by a superconducting solenoid. The iron of the flux return was instrumented by RPCs and LSTs for measuring the muons.

DATA COLLECTION

The data used in this analysis include 288 fb$^{-1}$ taken at the $\Upsilon(4S)$ resonance and 27 fb$^{-1}$ collected below the resonance.

The cuts applied for selecting the $D^0 \rightarrow \pi^+ \pi^- \pi^0$ candidates are [2]: (i) charged tracks with $p_T > 100$ MeV/c; (ii) particle identification compatible with a charged pion; (iii) $E_\gamma > 100$ MeV; (iv) $115 < M(\gamma\gamma) < 150$ MeV/c$^2$; (v) $E(\gamma\gamma) > 350$ MeV; (vi) $D^0$ vertex fit with $P(x^2) > 0.5%$; (vii) $1848 < M(D^0) < 1880$ MeV/c$^2$; (viii) $D^0$ generated by the $D^{*+}$ decay and selected with the cut $|M(D^{*+}) - M(D^0)| < 145.4| < 0.6$ MeV/c$^2$; (ix) $D^0$ momentum in the $e^+e^-$ c.m.s. $p^* > 2.77$ MeV/c; (x) exclusion of the events with $489 < M(\pi^+\pi^-\pi^0) < 508$ MeV/c$^2$.

The Dalitz-plot of the events selected with these cuts is shown in Fig. 1. It was already published in Refs. [3, 4]. It contains 44 780 ± 250 $D^0$ decays and an estimated contamination of 830 ± 250 events. The contamination was evaluated using the sideband $1930 < M(\pi^+\pi^-\pi^0) < 1990$ MeV/c$^2$.

This Dalitz-plot shows three $\rho$ bands and has low density at the centre and on the three diagonals. This structure is typical of a $\pi^+\pi^-\pi^0$ final state with $I^GJ^P = 0^-0^-$ [5]. The same properties were also visible in the CLEO analysis of the same decay [6].

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2 Charge conjugate decay modes are implicitly included.
FIGURE 1. The Dalitz-plot of the $D^0 \rightarrow \pi^+ \pi^- \pi^0$ decay. $s_+$ and $s_-$ are respectively $m^2(\pi^+ \pi^0)$ and $m^2(\pi^- \pi^0)$. The fine diagonal line at low $\pi^+ \pi^-$ mass corresponds to the events removed by the cut $489 < M(\pi^+ \pi^-) < 508$ MeV/$c^2$. The Dalitz-plot shows three diagonals with low density, indicating the dominance of the isospin zero.

DALITZ- PLOT ANALYSIS

The Dalitz plot density was fitted with the ansatz

$$D(s_+,s_-) = |\mathcal{N}|a_{NR}e^{i\phi_{NR}} + \sum_n A_n(s+s-) e^{i\phi_n}$$

where $s_+ = m^2(\pi^+ \pi^0)$, $s_- = m^2(\pi^- \pi^0)$, $\mathcal{N}$ is the normalization factor such that $\int D(s_+,s_-) ds_+ ds_- = 1$, and $A_n(s+s-)$ is the amplitude for the $n$th channel.

The amplitude for the decay $D^0 \rightarrow R_n\pi_3$, $R_n \rightarrow \pi_1\pi_2$ was calculated as

$$A_n(s+s-)=\frac{h_nS_J}{m_n^2-m_{12}^2-im_n\Gamma_n(m_{12})},$$

where $h_n$ is a normalization factor evaluated such that $\int |A_n(s_+,s_-)|^2 ds_+ ds_- = 1$, $m_n$ is the mass of the resonance $R_n$, $S_J$ is the spin factor for a resonance with spin $J$, and $\Gamma_n(m_{12})$ is the variable width of the resonance.

The functions $S_J$ and $\Gamma_n(m_{12})$ were written using the formulae written by the CLEO Collaboration in the analysis of the decay $D^0 \rightarrow K^- \pi^+ \pi^0$ [7].

The result of the fit is reported in Table 1. It shows that the $D^0$ Dalitz-plot is dominated by the three $\rho(770)$ channels, with a small contribution of the three $\rho(1700)$ channels and a very small contribution of the other channels. Furthermore, the sum of the fractions is 147.4%. This fact indicates that there is a strong negative interference between the 16 amplitudes of the channels used in the analysis.

ISOSPIN DECOMPOSITION

The first nine channels reported in Table 1 have the pions 1 and 2 in the isospin eigenstate $I_{12} = 1$, the subsequent six channel $I_{12} = 0$, and the last, i.e. the non resonant channel, is not an eigenstate of $I_{12}$. The Feynman diagrams of these channels are shown in Fig. 2. They can be grouped into four channels

$$|\rho^+\rho^-\rangle = |\rho(770)^+\rho^-\rangle + |\rho(1450)^+\pi^-\rangle + |\rho(1700)^+\pi^-\rangle = \frac{1}{\sqrt{2}}(|+\rangle |0-\rangle - |0+\rangle),$$

$$|\rho^0\rho^0\rangle = |\rho(770)^0\rho^0\rangle + |\rho(1450)^0\pi^0\rangle + |\rho(1700)^0\pi^0\rangle = \frac{1}{\sqrt{2}}(-\langle +0\rangle | -\rangle + |+0\rangle),$$
TABLE 1. Result of the fit of the \( D^0 \) Dalitz-plot showing the amplitude \( a_n \), the phase \( \phi_n \), and the fraction \( f_n = a^2_n \). The mass and width of the \( f_0(400) \) are 400 and 600 MeV/c². The masses and widths of the other mesons are taken by the 2006 issue of the Review of Particle Physics [8]. The phase of the \( \rho(770)^-\pi^- \) is fixed at 0°.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Amplitude ( a_n )</th>
<th>Phase ( \phi_n ) (°)</th>
<th>Fraction ( f_n ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho(770)^+\pi^- )</td>
<td>0.823 ± 0.000 ± 0.004</td>
<td>0</td>
<td>67.8 ± 0.0 ± 0.6</td>
</tr>
<tr>
<td>( \rho(770)^0\pi^0 )</td>
<td>0.512 ± 0.005 ± 0.011</td>
<td>16.2 ± 0.6 ± 0.4</td>
<td>26.2 ± 0.5 ± 1.1</td>
</tr>
<tr>
<td>( \rho(770)^-\pi^+ )</td>
<td>0.588 ± 0.007 ± 0.003</td>
<td>-2.0 ± 0.6 ± 0.6</td>
<td>34.6 ± 0.8 ± 0.3</td>
</tr>
<tr>
<td>( \rho(1450)^+\pi^- )</td>
<td>0.033 ± 0.011 ± 0.018</td>
<td>-146 ± 18 ± 14</td>
<td>0.11 ± 0.07 ± 0.12</td>
</tr>
<tr>
<td>( \rho(1450)^0\pi^0 )</td>
<td>0.055 ± 0.010 ± 0.006</td>
<td>10 ± 8 ± 13</td>
<td>0.30 ± 0.11 ± 0.07</td>
</tr>
<tr>
<td>( \rho(1450)^-\pi^+ )</td>
<td>0.134 ± 0.008 ± 0.004</td>
<td>16 ± 3 ± 3</td>
<td>1.79 ± 0.22 ± 0.12</td>
</tr>
<tr>
<td>( \rho(1700)^+\pi^- )</td>
<td>0.202 ± 0.017 ± 0.017</td>
<td>-17 ± 2 ± 2</td>
<td>4.1 ± 0.7 ± 0.7</td>
</tr>
<tr>
<td>( \rho(1700)^0\pi^0 )</td>
<td>0.224 ± 0.013 ± 0.022</td>
<td>-17 ± 2 ± 3</td>
<td>5.0 ± 0.6 ± 1.0</td>
</tr>
<tr>
<td>( \rho(1700)^-\pi^+ )</td>
<td>0.179 ± 0.011 ± 0.017</td>
<td>-50 ± 3 ± 3</td>
<td>3.2 ± 0.4 ± 0.6</td>
</tr>
<tr>
<td>( f_0(400)\pi^0 )</td>
<td>0.091 ± 0.006 ± 0.006</td>
<td>8 ± 4 ± 8</td>
<td>0.82 ± 0.10 ± 0.10</td>
</tr>
<tr>
<td>( f_0(980)\pi^0 )</td>
<td>0.050 ± 0.004 ± 0.004</td>
<td>-59 ± 5 ± 4</td>
<td>0.25 ± 0.04 ± 0.04</td>
</tr>
<tr>
<td>( f_0(1370)\pi^0 )</td>
<td>0.061 ± 0.009 ± 0.007</td>
<td>156 ± 9 ± 6</td>
<td>0.37 ± 0.11 ± 0.09</td>
</tr>
<tr>
<td>( f_0(1500)\pi^0 )</td>
<td>0.062 ± 0.006 ± 0.006</td>
<td>12 ± 9 ± 4</td>
<td>0.39 ± 0.08 ± 0.07</td>
</tr>
<tr>
<td>( f_0(1710)\pi^0 )</td>
<td>0.056 ± 0.006 ± 0.007</td>
<td>51 ± 8 ± 7</td>
<td>0.71 ± 0.07 ± 0.08</td>
</tr>
<tr>
<td>( f_2(1270)\pi^0 )</td>
<td>0.115 ± 0.003 ± 0.004</td>
<td>-171 ± 3 ± 4</td>
<td>1.32 ± 0.08 ± 0.10</td>
</tr>
<tr>
<td>nonresonant</td>
<td>0.092 ± 0.011 ± 0.007</td>
<td>-11 ± 4 ± 2</td>
<td>0.84 ± 0.21 ± 0.12</td>
</tr>
</tbody>
</table>

FIGURE 2. The Feynman diagrams for the first fifteen channels listed in Table 1. (a) \( \{|\rho^+\pi^-\} \). (b) \( \{|\rho^-\pi^+\} \). (c) and (d) \( \{|\rho^0\pi^0\} \) and \( \{|f\pi^0\} \). \( \rho \) indicates one of the three mesons \( \rho(770), \rho(1450), \) and \( \rho(1700) \). \( f \) indicates one of the six mesons \( f_0(400), f_0(980), f_0(1370), f_0(1500), f_0(1710), \) and \( f_2(1270) \).

\[
\begin{align*}
|\{\rho\}^{-\pi^+}\rangle &= |\rho(770)^-\pi^+\rangle + |\rho(1450)^-\pi^+\rangle + |\rho(1700)^-\pi^+\rangle = \frac{1}{\sqrt{2}} (|0^+\rangle - |0^-\rangle), \\
|\{f\} \pi^0\rangle &= |f_0(400)\pi^0\rangle + |f_0(980)\pi^0\rangle + |f_0(1370)\pi^0\rangle + |f_0(1500)\pi^0\rangle + |f_0(1710)\pi^0\rangle + |f_2(1710)\pi^0\rangle = \frac{1}{\sqrt{2}} (|0^-\rangle + |0^-\rangle),
\end{align*}
\]

where \( |q_1 q_2 q_3\rangle \) indicates the state \( |\pi^{q_1}\rangle |\pi^{q_2}\rangle |\pi^{q_3}\rangle \), \( q_i = +, -, 0 \) being the charge of the \( i \).th pion. The amplitudes of these four states are obtained by summing the amplitudes of the channels in the right side of (4).

We use the symbols \( I|I_{12}; l_z \rangle \) for the isospin eigenstates of the \( 3\pi \) final states. Here \( I \) is the total isospin, \( I_{12} \) is the isospin of interacting pion pair 12, and \( l_z \) is the third component of the isospin. The formulae of these eigenstates with
I_c = 0 can be found in Eq. (3) of Ref. [4].

Using the relations (4), the three eigenstates with \( I_{12} = 1 \) can be written such a way

\[
|2(1);0\rangle = \frac{1}{\sqrt{6}} \left( (|\rho\rangle^+\pi^-) - 2(|\rho\rangle^0\pi^0) + (|\rho\rangle^-\pi^+) \right),
\]

\[
|1(1);0\rangle = \frac{1}{\sqrt{2}} \left( (|\rho\rangle^+\pi^-) - (|\rho\rangle^-\pi^+) \right),
\]

\[
|0(1);0\rangle = \frac{1}{\sqrt{3}} \left( (|\rho\rangle^+\pi^-) + (|\rho\rangle^0\pi^0) + (|\rho\rangle^-\pi^+) \right).
\]

The non resonant channel \( |\text{NR}\rangle \) can have two interpretations: (i) it corrects the \( |\{f\}\pi^0\rangle \) amplitude that was not well parametrized; (ii) it describes a point-like interaction that generates a uniform \( \pi^+\pi^-\pi^0 \) final state. In the case (i), the channel \( |\text{NR}\rangle \) has \( I_{12} = 0 \). Therefore, the contribution of the isospin state \( |1(0);0\rangle \) to the \( D^0 \to \pi^+\pi^-\pi^0 \) decay is

\[
P_{(+0)}|1(0);0\rangle = |\{f\}\pi^0\rangle + |\text{NR}\rangle,
\]

\( P_{(+0)} \) being the projection operator of an isospin eigenfunction into the final state \( \pi^+\pi^-\pi^0 \).

In the case (ii), the isospin wave functions of \( |\text{NR}\rangle \) is symmetrical. There are two \( 3\pi \) symmetrical isospin eigenstates. One is \( |3(2);0\rangle \), the other is the \( I = 1 \) symmetric state

\[
|1(S);0\rangle = \frac{2}{3} |1(2);0\rangle + \frac{\sqrt{5}}{3} |1(0);0\rangle
\]

\[= \frac{1}{\sqrt{15}} \left( (|0+0\rangle + |0+0\rangle + |0+0\rangle + |0+0\rangle + |0+0\rangle - 3|000\rangle) \right) .
\]

The analysis carried out in Ref. [4] was based on the assumption that the isospin wave-function of the non resonant channels was \( |1(S);0\rangle \), because a state generated by a point-like four quark interaction cannot have \( I = 3 \). This interpretation predicts

\[
P_{(+0)}|1(0);0\rangle = |\{f\}\pi^0\rangle + \frac{\sqrt{5}}{3} |\text{NR}\rangle,
\]

\[
P_{(+0)}|1(2);0\rangle = \frac{2}{3} |1(2);0\rangle.
\]

The results are reported in Table 2.

These results allow to estimate the branching ratio \( \mathcal{B}(D^0 \to 3\pi^0) \). The branching ratio of the decay (1) is \( \mathcal{B}(D^0 \to \pi^+\pi^-\pi^0) = (1.44 \pm 0.06)\% \) [9] and Eq. (3) of Ref. [4] tell us that the isospin eigenstates \( |1(2);0\rangle \) and \( |1(0);0\rangle \) decays into \( 3\pi^0 \) and \( \pi^+\pi^-\pi^0 \) respectively with the ratios 4:11 and 1:2. Therefore, from the fractions \( f \) reported in the last column of Table 2, we obtain

\[
\mathcal{B}(D^0 \to 3\pi^0) = \mathcal{B}(D^0 \to \pi^+\pi^-\pi^0) \left[ \frac{4}{11} f_{|1(2);0\rangle} + \frac{1}{2} f_{|1(0);0\rangle} \right] = (8.3 \pm 0.8) \times 10^{-5}.
\]

This estimate is in agreement with the measure of CLEO \( \mathcal{B}(D^0 \to 3\pi^0) < 3.5 \times 10^{-4} \) [10].

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3 The limited number of pages do not permit to report the formulae of these isospin eigenstates.
INTERPRETATION AND PREDICTIONS

A $\pi^+\pi^-\pi^0$ final state generated by a pseudoscalar meson decay has $J^P = 0^-$, $G$-parity $-1$, and charge conjugation $C = G(-1)^I$. The isospin states $|0(1);0\rangle$ and $|2(1);0\rangle$ have $CP = +1$ and the other three states with $I = 1$ have $CP = -1$. Therefore, the results shown in Table 2 tell us that the decay $D^0 \to \pi^+\pi^-\pi^0$ proceeds for $(98.11 \pm 0.11)\%$ via the $CP = +1$ eigenstate

$$D_1 = \frac{1}{\sqrt{2}}(|D^0\rangle + |\bar{D}^0\rangle).$$

The tree graphs shown in Fig. 2 do not predict the dominance of a pure isospin state. Then, if the $I = 0$ dominance is not coincidental, there should be a physical explanation. A possible interpretation is that the $I = 0$ dominance is due to a final state interaction with an $I^G J^P C = 0^- 0^- -$ meson that resonates with the four quark generated by the $D^0$ decay. Such a meson must be exotic because a $q\bar{q}$ pair cannot have these quantum number. It could be a state $2q2\bar{q}$.

If this interpretation is right, this meson should also have other decays. The principal candidates are the final states $2\pi^+2\pi^-\pi^0$ and $\pi^+\pi^-3\pi^0$ because the analysis of the $D^0 \to \pi^+\pi^-\pi^0$ found a non negligible contributions of the channels $\rho(1450)\pi$ and $\rho(1700)\pi$, and the mesons $\rho(1450)$ and $\rho(1700)$ decay also in $4\pi$. Furthermore, it is possible that this meson could also decay into $K\bar{K}\pi$.

CONCLUSIONS

We see a strange behaviour in the $D^0 \to \pi^+\pi^-\pi^0$ Dalitz-plot: this decay is dominated by the $I = 0$ final state [3, 4]. We take this as a hint of something interesting that deserves further studies. We need to analyze the decays $D^0 \to K\bar{K}\pi$ and $D^0 \to 5\pi$ to understand if the $I = 0$ dominance in $D^0 \to \pi^+\pi^-\pi^0$ is coincidental or it is a general rule not predicted by the standard model.

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