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

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Abstract

The Dalitz-plot of the decay $D^0 \to \pi^+\pi^-\pi^0$ measured by the BABAR collaboration shows the structure of a final state having quantum numbers $I^G J^{PC} = 0^- 0^{--}$. 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.

1 Introduction

This communication reports the results of the analysis of the Cabibbo suppressed decay[1]

$$D^0 \to \pi^+\pi^-\pi^0 \tag{1}$$

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 *elctromagnetic 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.

[1] Charge conjugate decay modes are implicitely included.

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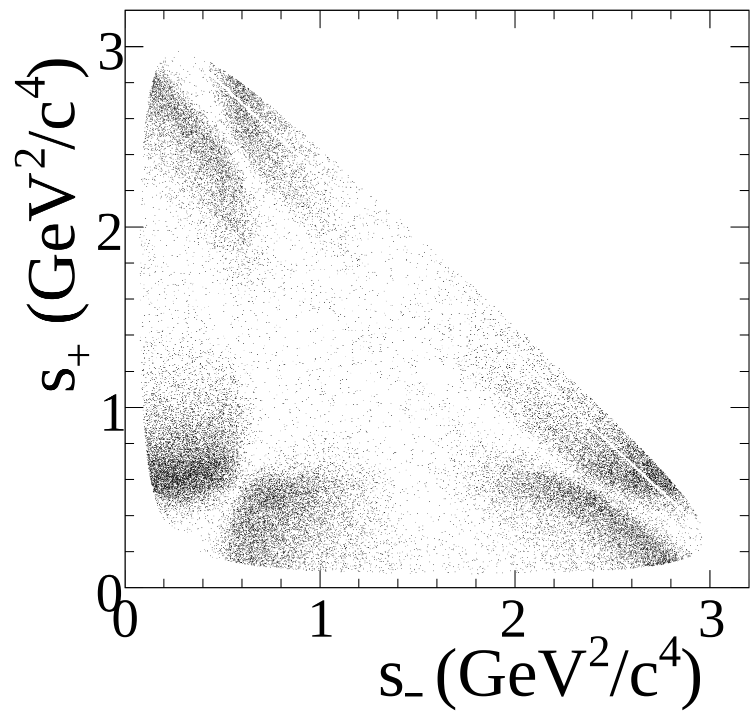

Figure 1: The Dalitz-plot of the $D^0 \to \pi^+\pi^-\pi^0$ decay. s_+ and s_- are respectively $m^2(\pi^+\pi^0)$ and $m^2(\pi^-\pi^0)$. The fine diagonal line at low $\pi^+\pi^-$ mass corresponds to the events removed by the cut $489 < M(\pi^+\pi^-) < 508$ MeV/c^2. The Dalitz-plot shows three diagonals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

2 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 $D^0 \to \pi^+\pi^-\pi^0$ candidates are [2]: (i) charged tracks with $p_T > 100$ MeV/c; (ii) particle identification compatibile 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 $P(\chi^2) > 0.5\%$; (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 $489 < M(\pi^+\pi^-) < 508$ 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 $44\,780 \pm 250$ 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 ρ 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 $I^G J^P = 0^-0^-$ [5]. The same properties were also visible in the CLEO analysis of the same decay [6].

3 Dalitz-plot analysis

The Dalitz plot density was fitted with the ansatz

$$D(s_+, s_-) = \mathcal{N}|a_{\rm NR}e^{i\phi_{\rm NR}} + \sum_n a_n e^{i\phi_n} A_n(s_+ s_-)|^2, \qquad (2)$$

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 $D^0 \to R_n\pi_3$, $R_n \to \pi_1\pi_2$ was calculated as

$$A_n(s_+ s_-) = \frac{h_n S_J}{m_n^2 - m_{12}^2 - i m_n \Gamma_n(m_{12})}, \qquad (3)$$

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 $D^0 \to K^-\pi^+\pi^0$ [7]

The result of the fit is reported in Table I. It shows that the D^0 Dalitz-plot is dominated by the three $\rho(770)\pi$ channels, with a small contribution of the three $\rho(1700)\pi$ 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.

4 Isospin decomposition

The first nine channels reported in Table I 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

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

Table 1: Result of the fit of the D^0 Dalitz-plot showing the amplitude a_n, the phase ϕ_n and the fraction $f_n = a_n^2$. The mass and width of the $f_0(400)$ are 400 and 600 MeV/c^2. 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°.

$$
\begin{aligned}
|\{\rho\}^+\pi^-\rangle &= |\rho(770)^+\pi^-\rangle + |\rho(1450)^+\pi^-\rangle + |\rho(1700)^+\pi^-\rangle = \\
&\quad \frac{1}{\sqrt{2}}\,(|+0-\rangle - |0+-\rangle), \\
|\{\rho\}^0\,\pi^0\rangle &= |\rho(770)^0\pi^0\rangle + |\rho(1450)^0\pi^0\rangle + |\rho(1700)^0\pi^0\rangle = \\
&\quad \frac{1}{\sqrt{2}}\,(|-+0\rangle - |+-0\rangle), \\
|\{\rho\}^-\pi^+\rangle &= |\rho(770)^-\pi^+\rangle + |\rho(1450)^-\pi^+\rangle + |\rho(1700)^-\pi^+\rangle = \\
&\quad \frac{1}{\sqrt{2}}\,(|-0+\rangle - |0-+\rangle), \\
|\{f\}\,\pi^0\rangle &= |f_0(400)\pi^0\rangle + |f_0(980)\pi^0\rangle + |f_0(1370)\pi^0\rangle + \\
&\quad |f_0(1500)\pi^0\rangle + |f_0(1710)\pi^0\rangle + |f_2(1710)\pi^0\rangle = \\
&\quad \frac{1}{\sqrt{2}}\,(|+-0\rangle + |-+0\rangle),
\end{aligned}
\tag{4}
$$

where $|q_1q_2q_3\rangle$ 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 $|I(I_{12}); I_z\rangle$ for the isospin eigenstates of the 3π final

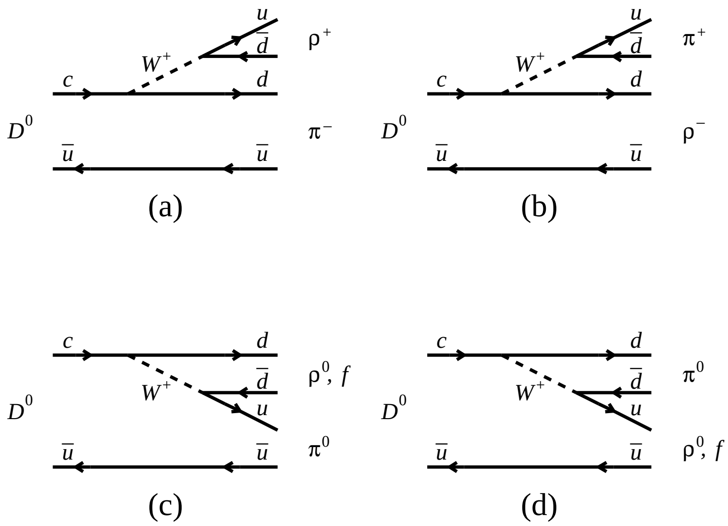

Figure 2: The Feynman diagrams for the first fitheen channels listed in Table I. (a) $|\{\rho\}^+\pi^-\rangle$. (b) $|\{\rho^-\}\pi^+\rangle$. (c) and (d) $|\{\rho^0\}\pi^0\rangle$ and $|\{f\}\pi^0\rangle$. $\{\rho\}$ indicates one of the three mesons $\rho(770)$, $\rho(1450)$, and $\rho(1700)$. $\{f\}$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

states. Here I is the total isospin, I_{12} is the isospin of interacting pion pair 12, and I_z is the third component of the isospin. The formulae of these eigenstates with $I_z = 0$ 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

$$\begin{aligned}
|2(1);0\rangle &= \frac{1}{\sqrt{6}}\left(|\{\rho\}^+\pi^-\rangle - 2|\{\rho\}^0\pi^0\rangle + |\{\rho\}^-\pi^+\rangle\right), \qquad (5)\\
|1(1);0\rangle &= \frac{1}{\sqrt{2}}\left(|\{\rho\}^+\pi^-\rangle - |\{\rho\}^-\pi^+\rangle\right),\\
|0(1);0\rangle &= \frac{1}{\sqrt{3}}\left(|\{\rho\}^+\pi^-\rangle + |\{\rho\}^0\pi^0\rangle + |\{\rho\}^-\pi^+\rangle\right).
\end{aligned}$$

The *non resonant* channel $|\mathrm{NR}\rangle$ 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 $|\mathrm{NR}\rangle$ 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

$$P_{\{+-0\}}|1(0);0\rangle = |\{f\}\pi^0\rangle + |\mathrm{NR}\rangle,$$

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

Isospin wave function	Amplitude	Phase (°)	Fraction (%)
$\|2(1);0\rangle$	0.1368 ± 0.0016	-42.5 ± 0.7	1.87 ± 0.04
$\|1(2);0\rangle$	0.0617 ± 0.0022	-8.9 ± 2.6	0.38 ± 0.03
$\|1(1);0\rangle$	0.0799 ± 0.0023	18.0 ± 2.0	0.64 ± 0.04
$\|1(0);0\rangle$	0.0936 ± 0.0051	14.5 ± 2.4	0.87 ± 0.10
$\|0(1);0\rangle$	0.9810 ± 0.0006	0	96.23 ± 0.12

Table 2: Amplitudes, phases and fractions of the five isospin channels contributing to the $D^0 \to \pi^+\pi^-\pi^0$ decay. The errors are only statistical. The phase of the state $|0(1);0\rangle$ is fixed at 0°.

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

$$\begin{aligned} |1(S);0\rangle \quad &\equiv \quad \frac{2}{3}\,|1(2);0\rangle + \frac{\sqrt{5}}{3}\,|1(0);0\rangle = \frac{1}{\sqrt{15}}\,(|+0-\rangle + |+-0\rangle + \\ &|0+-\rangle + |0-+\rangle + |-+0\rangle + |-0+\rangle - 3|000\rangle). \end{aligned}$$

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

$$\begin{aligned} P_{\{+-0\}}|1(0);0\rangle \quad &= \quad |\{f\}\pi^0\rangle + \frac{\sqrt{5}}{3}\,|\mathrm{NR}\rangle, \\ P_{\{+-0\}}|1(2);0\rangle \quad &= \quad \frac{2}{3}\,|NR\rangle. \end{aligned}$$

The results are reported in Table II.

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 coluumn of Table II, we obtain

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

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

5 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 II 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 $I^G J^{PC} = 0^- 0^{--}$ 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 pricipal 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 4π. Furthermore, it is possible that this meson could also decay into $K\bar{K}\pi$.

6 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 someting 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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