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

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Outline

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Introduction: the detector (1)

This talks reports the results of the *isospin analysis* of the final state in the decay $D^0 \rightarrow \pi^+ \pi^- \pi^0$. The data were collected by the *BABAR* detector at the $e^+e^-$ PEP-II collider. Most of the *BABAR* data were taken at the $Y(4S)$ resonance to study the $B$ mesons. The *charm mesons* were generated by the decay of the $B$ mesons or by the continuum, i.e. by the $e^+e^-$ annihilations into $cc$. 
Introduction: the detector (2)

The charged tracks were measured by a *silicon vertex tracker* (SVT) and by a *drift chamber* (DCH), and identified by a *ring-imaging Cherenkov detector* (DIRC). The photons were measured by an *electromagnetic calorimeter* (EMC) 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: cuts

The data used in this analysis include 288 fb\(^{-1}\) taken at the \(Y(4S)\) resonance and 27 fb\(^{-1}\) collected 40 MeV below the resonance.

The cuts applied for selecting the \(D^0 \rightarrow \pi^+ \pi^- \pi^0\) candidates are:

- \(D^0\) generated by the \(D^{*+}\) decay;
- \textit{charged tracks} with \(p_T > 100\) MeV/c and PID compatible with \(\pi\);
- \(E_\gamma > 100\) MeV;
- \(115 < M(\gamma\gamma) < 150\) MeV/c\(^2\) and \(E(\gamma\gamma) > 350\) MeV;
- \(D^0\) vertex fit with \(P(\chi^2) > 0.5\%\);
- \(1848 < M(D^0) < 1880\) MeV/c\(^2\);
- \(|M(D^{*+}) - M(D^0) - 145.4| < 0.6\) MeV/c\(^2\);
- \(p^*(D^0) > 2.77\) GeV/c;
- exclusion of the events with \(489 < M(\pi^+\pi^-) < 508\) MeV/c\(^2\).
Data collection: Dalitz plot

The efficiency has been evaluated with a Montecarlo and parametrized with a third degree two dimensional polynomial.

The contamination has been evaluated from the sideband $1930 < M(\pi^+\pi^-\pi^0) < 1990 \text{ MeV}/c^2$.

Estimated $D^0$: $44,780 \pm 250$ events

background: $830 \pm 250$ events

Dalitz plot published in


$$s_+ = m^2(\pi^+\pi^0) \quad s_- = m^2(\pi^-\pi^0)$$
Data collection: \( I = 0 \) dominance

One sees immediately:

- 3 \( \rho \pi \) bands.
- Low density at the centre and on the three diagonals,
- The structure is predicted by C. Zemach, PR 133, B1201 (1964) for \( IJ^p = 00^- \).

From Zemach
Data collection: CLEO results

The evidence of the $I = 0$ dominance was already visible in two paper of CLEO with 1917 events and a background of about 340 events.

*CLEO, Conference HEP 2003. Aachen, hep-ex/0306048*

*CLEO, PRD 72, 031102 (2005)*

**BUT CLEO DID NOT CLAIM TO HAVE OBSERVED THE $I = 0$ DOMINANCE!**
Dalitz plot fit: parametrization

The Dalitz plot has been fitted with a sum of resonances

\[
f(s_+, s_-) = \frac{1}{\mathcal{N}} \left[ a_{NR} e^{i\phi_{NR}} + \sum_n a_n e^{i\phi_n} A_n(s_+, s_-) \right]
\]

The amplitudes \( A_n(s_+, s_-) \) are Breit-Wigner functions with the \textit{PDG 2006} masses and widths. The spin-factors are written using the formulae reported in \textit{CLEO, PRD 63, 092001 (2001)}. 
The results of the Dalitz plot fit were reported in \textit{PRL 99}, 251801(2007).

To be remarked:

- Small $\rho'$ fractions
- Large interference:
  - Sum of fractions $(147.9 \pm 2.4)\%$

\begin{table}[h]
\centering
\caption{Result of the fit to the $D^{*+} \to D^0 \pi^+$ sample, showing the amplitudes ratios $R_r = a_r/a_{\rho^+(770)}$, phase differences $\Delta \phi_r = \phi_r - \phi_{\rho^+(770)}$, and fit fractions $f_r = \int |a_r A_r(s_+,s_-)|^2 ds_+ ds_-$. The first (second) errors are statistical (systematic). We take the mass (width) of the $\sigma$ meson to be 400(600) MeV/c$^2$.}
\begin{tabular}{|c|c|c|c|}
\hline
State & $R_r$ (%) & $\Delta \phi_r$ (°) & $f_r$ (%) \\
\hline
$\rho^+(770)$ & 100 & 0 & 67.8 ± 0.0 ± 0.6 \\
$\rho^0(770)$ & 58.8 ± 0.6 ± 0.2 & 16.2 ± 0.6 ± 0.4 & 26.2 ± 0.5 ± 1.1 \\
$\rho^-(770)$ & 71.4 ± 0.8 ± 0.3 & −2.0 ± 0.6 ± 0.6 & 34.6 ± 0.8 ± 0.3 \\
$\rho^+(1450)$ & 21 ± 6 ± 13 & −146 ± 18 ± 24 & 0.11 ± 0.07 ± 0.12 \\
$\rho^0(1450)$ & 33 ± 6 ± 4 & 10 ± 8 ± 13 & 0.30 ± 0.11 ± 0.07 \\
$\rho^-(1450)$ & 82 ± 5 ± 4 & 16 ± 3 ± 3 & 1.79 ± 0.22 ± 0.12 \\
$\rho^+(1700)$ & 225 ± 18 ± 14 & −17 ± 2 ± 3 & 4.1 ± 0.7 ± 0.7 \\
$\rho^0(1700)$ & 251 ± 15 ± 13 & −17 ± 2 ± 2 & 5.0 ± 0.6 ± 1.0 \\
$\rho^-(1700)$ & 200 ± 11 ± 7 & −50 ± 3 ± 3 & 3.2 ± 0.4 ± 0.6 \\
$f_0(980)$ & 1.50 ± 0.12 ± 0.17 & −59 ± 5 ± 4 & 0.25 ± 0.04 ± 0.04 \\
$f_0(1370)$ & 6.3 ± 0.9 ± 0.9 & 156 ± 9 ± 6 & 0.37 ± 0.11 ± 0.09 \\
$f_0(1500)$ & 5.8 ± 0.6 ± 0.6 & 12 ± 9 ± 4 & 0.39 ± 0.08 ± 0.07 \\
$f_0(1710)$ & 11.2 ± 1.4 ± 1.7 & 51 ± 8 ± 7 & 0.31 ± 0.07 ± 0.08 \\
f_2(1270) & 104 ± 3 ± 21 & −171 ± 3 ± 4 & 1.32 ± 0.08 ± 0.10 \\
$\sigma(400)$ & 6.9 ± 0.6 ± 1.2 & 8 ± 4 ± 8 & 0.82 ± 0.10 ± 0.10 \\
Nonresonant & 57 ± 7 ± 8 & −11 ± 4 ± 2 & 0.84 ± 0.21 ± 0.12 \\
\hline
\end{tabular}
\end{table}
Isospin analysis: wave functions (1)

The analysis was based on amplitudes with two interacting pions $[\rho\pi, f_0\pi, f_2\pi] + \text{a non-resonant term}$. They are isospin eigenstates of the first two pion $I_{12}$, but are not eigenstates of the $3\pi$ state.

The isospin wave function of a $3\pi$ state $|I(\iota); I_3> \text{ depends on three quantum numbers:}$

- the total isospin $I$
- the third component $I_3$ (i.e. the charge)
- another quantum number $\iota$

The logical choice for the third quantum number is to use the isospin $I_{12}$ of the fist two pion. They, for $I_3 = 0$, are
Isospin analysis: wave functions (2)

\[|3(2);0> = \frac{1}{\sqrt{10}} (|0+0> + |0-0> + |0+0> - |0-0> + |0+0> + |0-0> + |0+0> + |0-0> + |0+0> + 2|000>)\]
\[|2(2);0> = \frac{1}{2} (|0+0> + |0-0> - |0+0> + |0-0> - |0+0> + |0-0> + |0+0> - |0-0>)\]
\[|2(1);0> = \frac{1}{\sqrt{12}} (|0+0> + |0-0> - |0+0> + |0-0> - |0+0> + |0-0> + |0+0> - |0-0>)\]
\[|1(2);0> = \frac{1}{\sqrt{60}} (3|0+0> - 2|0-0> + 3|0+0> + 3|0-0> - 3|0+0> + 3|0-0> - 4|000>)\]
\[|1(1);0> = \frac{1}{2} (|0+0> + |0-0> - |0+0> + |0-0> - |0+0> + |0-0> + |0+0>)\]
\[|1(0),0> = \frac{1}{\sqrt{3}} (|0+0> + |0-0> - |000>)\]
\[|0(1);0> = \frac{1}{\sqrt{6}} (|0+0> + |0-0> - |0+0> + |0-0> + |0+0> + |0-0> + |0+0>)\]

The states \(|3(2);0>, |2(2);0>, \text{ and } |1(2);0>\) could be ignored if one believes that the contribution of \(\pi\pi I = 2\) interaction is negligible. The non-resonant term can have two contributions: one is the state \(|3(2);0>\), the other is the \(I = 1\) symmetrical combination.

\[|1(S);0> = \frac{2}{3} |1(2);0> + \frac{\sqrt{5}}{3} |1(0);0>\]
\[= \frac{1}{\sqrt{15}} (|0+0> + |0-0> + |0+0> + |0-0> + |0+0> + |0-0> + |0+0> + |0-0> + |0+0> + 3|000>)\]
Isospin analysis: isospin amplitudes (1)

The isospin amplitudes have been evaluated in the paper PRD 78, 014015 (2008) written by Gaspero, Meadows, Mishra and Soffer. Using the previous isospin wave functions and assuming that isospin wave function of the non-resonant term is $|1(S);0>$ we have:

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

\[
|1(2);0> = \frac{3}{\sqrt{10}} |NR > - \sqrt{\frac{5}{6}} |f\pi^0> - \frac{2}{\sqrt{15}} |000>
\]

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

\[
|1(0);0> = \sqrt{\frac{2}{3}} |f\pi^0> - \frac{1}{\sqrt{3}} |000>
\]

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

I am not convinced that the non resonant amplitude has isospin wavefunction $|1(S);0>$. I think that it has isospin wave function $|1(0);0>$.
Isospin analysis: isospin amplitudes (2)

It follows

\[ C_{1(2)} = \frac{\sqrt{10}}{3} B_{NR}, \]
\[ C_{2(1)} = \frac{1}{\sqrt{6}} (B_{\rho^+\pi^-} - 2B_{\rho^0\pi^0} + B_{\rho^-\pi^+}), \]
\[ C_{1(1)} = \frac{1}{\sqrt{2}} (B_{\rho^+\pi^-} - B_{\rho^-\pi^+}), \]
\[ C_{0(1)} = \frac{1}{\sqrt{3}} (B_{\rho^+\pi^-} + B_{\rho^0\pi^0} + B_{\rho^-\pi^+}), \]
\[ C_{1(0)} = \sqrt{\frac{3}{2}} B_{f\pi^0} + \sqrt{\frac{5}{6}} C_{1(2)}, \]

The coefficients $B'$s are the sum of the fitted amplitudes with the correct normalization.

The results reported in *PRD 78, 014015 (2008)* are

\[ C_{1(2)} = (0.0629 \pm 0.0028) \exp[i(-8.9 \pm 2.6)^\circ], \]
\[ C_{2(1)} = (0.1395 \pm 0.0016) \exp[i(-42.5 \pm 0.7)^\circ], \]
\[ C_{1(1)} = (0.0814 \pm 0.0023) \exp[i(18.0 \pm 2.0)^\circ], \]
\[ C_{0(1)} = 1, \]
\[ C_{1(0)} = (0.0954 \pm 0.0052) \exp[i(14.5 \pm 2.4)^\circ]. \]
Isospin analysis: results

Therefore, the fractions \( f_{I(1)} = |C_{I(1)}|^2 \) of these isospin contributions are:

\[
\begin{align*}
  f_{2(1)} &= (1.87 \pm 0.02)\% \\
  f_{1(2)} &= (0.38 \pm 0.02)\% \\
  f_{1(1)} &= (0.64 \pm 0.02)\% \\
  f_{1(0)} &= (0.88 \pm 0.05)\% \\
  f_{0(1)} &= (96.23 \pm 0.06)\% \quad \text{!!!}
\end{align*}
\]

(Statistical errors only)

The relation between charge conjugation and G-parity is

\[ G = C(-1)^I \]

Then \( |0(1)\rangle \) and \( |2(1)\rangle \) have \( CP = + \) while the three states with \( I = 1 \) have \( CP = - \)

It means that the decay \( D^0 \rightarrow \pi^+ \pi^- \pi^0 \) proceeds for about 98% through the \( CP = + \) eigenstate \( D_1 = 1/\sqrt{2} \ (|D^0\rangle + \overline{|D^0\rangle}) \)
Interpretation: tree graphs (1)

There are 4 quarks. Then no $I_{12} = 2$ states are allowed.

The states with $I_{12} = 1$ are sum of $\rho \pi$ states.

The states with $I_{12} = 0$ are sum of $f_0 \pi^0$ and $f_2 \pi^0$ states.

Red lines: $\pi$; Blue lines: $\rho, \rho', f_0, f_2$
Interpretation: tree graphs (2)

The tree graphs do not predict the dominance of a pure isospin state. Furthermore, the same graphs are responsible for the decays of the mesons $K^0_L, K^0_S, B^0$ into $3\pi$ that are not dominated by the final state $I = 0$!

Then, if the $I = 0$ dominance in the $D^0$ decay is not coincidental, there should be a physical explanation.

WHAT IS IT?
Interpretation: an exotic state?

A possible interpretation is that there is a final state interaction due to an $I^G J^{PC} = 0^- 0^- 0^-$ meson that resonates with the decay products of the $D^0$. This meson $T^0$ could be a state $2q 2\bar{q}$:

If this interpretation is right it would be a clear evidence for the existence of a $2q 2\bar{q}$ meson!
Further studies: $D^0 \to \pi^0\pi^0\pi^0$

The state $|000\rangle$ could be generated by $|3(2);0\rangle$, $|1(2);0\rangle$, and $|1(0);0\rangle$. 

*Our isospin analysis* finds the contributions $f_{3(2)} = 0$, $f_{1(2)} = 0.38\%$ and $f_{1(0)} = 0.88\%$ to $\pi^+\pi^-\pi^0$.

Since $\pi^0\pi^0\pi^0 : \pi^+\pi^-\pi^0 = 4 : 11$ for $|1(2);0\rangle$ and $1 : 2$ for $|1(0);0\rangle$, then

$$B(D^0 \to \pi^0\pi^0\pi^0) / B(D^0 \to \pi^+\pi^-\pi^0) = \frac{4}{11} f_{1(2)} + (1/2) f_{1(0)} \approx 0.58\%$$

in agreement with *PDG 2008* that reports $B(D^0 \to \pi^0\pi^0\pi^0) < 3.5 \times 10^{-4}$ and $B(D^0 \to \pi^+\pi^-\pi^0) = (1.44 \pm 0.06)\%$. It follows

$$B(D^0 \to \pi^0\pi^0\pi^0) \approx 0.0058 \quad B(D^0 \to \pi^+\pi^-\pi^0) \approx 5 \times 10^{-5}$$
Further studies: $D^0 \to 5\pi$ (1)

Decays:

1. $D^0 \to 2\pi^+ 2\pi^- \pi^0$
2. $D^0 \to \pi^+ \pi^- 3\pi^0$
3. $D^0 \to 5\pi^0$

They could be produced by:

- $\rho'\pi$, $\omega 2\pi$, $a_1 2\pi$, $f_0(1370)\pi^0$, etc.

The analysis of $D^0 \to \pi^+ \pi^- \pi^0$ has found the production of $\rho(1450)\pi$ and $\rho(1750)\pi$; these channels have $I = 0$.

$\rho(1450)$ and $\rho(1750)$ can decay into $4\pi$.

$\rightarrow I = 0$ could also dominate the $D^0$ decays into $5\pi$. 
Further studies: $D^0 \rightarrow 5\pi$ (2)

Only existing measurements:

*CLEO PRL 96, 081802 (2006)*

$B(D^0 \rightarrow 2\pi^+2\pi^-\pi^0) = (0.41 \pm 0.05)\%$

$B(D^0 \rightarrow \omega\pi^+\pi^-) = (0.17 \pm 0.05)\%$

The other branching ratios have not yet been measured. I suppose that $B(D^0 \rightarrow \pi^+\pi^-3\pi^0)$ is of the order of $B(D^0 \rightarrow 2\pi^+2\pi^-\pi^0)$. Therefore I suggest:

**STUDY** $D^0 \rightarrow 5\pi$ !!!
Further studies: $D^0 \rightarrow K\bar{K}\pi$

Branching ratios from *PDG 2008*:

- $\mathcal{B}(D^0 \rightarrow K^+K^0_s\pi^-) = (0.27 \pm 0.05)\%$
- $\mathcal{B}(D^0 \rightarrow K^+K^0\pi^0) = (0.329 \pm 0.014)\%$
- $\mathcal{B}(D^0 \rightarrow \phi\pi^0; \phi \rightarrow K^+K^-) = (0.061 \pm 0.006)\%$
- $\mathcal{B}(D^0 \rightarrow K^0_sK^-\pi^+) = (0.35 \pm 0.05)\%$
- $\mathcal{B}(D^0 \rightarrow K^0_sK^0_s\pi^0) < 0.059\%$
- $\mathcal{B}(D^0 \rightarrow K^0_sK^0_s\pi^0)$ unmeasured

A coupled analysis of these decays could separate the $I = 0$ and $I = 1$ contributions. ($I = 2$ is not allowed for a $u\bar{u}s\bar{s}$ state.)
Conclusions

1) We see a strange behaviour in the $D^0 \rightarrow \pi^+ \pi^- \pi^0$ Dalitz plot.

2) The $D^0 \rightarrow \pi^+ \pi^- \pi^0$ decay is dominated by $I = 0$ [PRL 99, 251801 (2007) and PRD 78, 014015 (2008)].

3) We take this as a hint of something interesting that deserves further studies.

4) We need to analyze the decays

   $D^0 \rightarrow 5\pi$

   $D^0 \rightarrow KK\pi$

   to understand if the dominance of $I = 0$ in $D^0 \rightarrow \pi^+ \pi^- \pi^0$ is coincidental or it is a general rule NOT predicted by the SM.
Backup slides
Mass distributions
Efficiency evaluation

dimensions

third polynomial in two

M. Gaspero, HADRON 2009 Conference, TALLAHASSEE – 30 November 2009