Looking for $\Delta I = 5/2$ amplitude components in $B \rightarrow \pi\pi$ and $B \rightarrow \rho\rho$ experiments

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Abstract

We discuss how experiments measuring $B \rightarrow \pi\pi$ and $B \rightarrow \rho\rho$ may be used to search for a $\Delta I = 5/2$ amplitude component. This component could be the explanation for a recent (albeit very tentative) hint from $B(\bar{B}) \rightarrow \rho\rho$ decays that the isospin triangles do not close.

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Within the standard model (SM), CP violation is due to a complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix. This phase information can be elegantly encoded in the unitarity triangle $\Delta_1, \Delta_2$, in which the interior CP-violating angles are called $\alpha, \beta$ and $\gamma$. Independent measurements of the sides and angles of the unitarity triangle allow tests of the SM explanation of CP violation.

The canonical decay mode for measuring $\alpha$ is $B^0(t) \to \pi^+\pi^-$. However, due to the fact that this decay receives both tree and penguin contributions, $\alpha$ cannot be extracted cleanly – there is penguin “pollution.” On the other hand, if one uses isospin to combine measurements of $B^+ \to \pi^+\pi^0$, $B^0(t) \to \pi^+\pi^-$ and $B^0(t) \to \pi^0\pi^0$, as well as the CP-conjugate decays, then the penguin pollution can be removed, and $\alpha$ obtained cleanly [3].

The isospin analysis goes as follows. Due to Bose statistics and the fact that the final-state pions come from the decay of a spinless state, they must be in a symmetric isospin configuration. As a result, the final states are

$$\langle \pi^0\pi^0 \rangle = \sqrt{\frac{2}{3}} \langle 2, 0 \rangle - \sqrt{\frac{1}{3}} \langle 0, 0 \rangle,$$
$$\langle \pi^+\pi^- \rangle = \sqrt{\frac{1}{3}} \langle 2, 0 \rangle + \sqrt{\frac{2}{3}} \langle 0, 0 \rangle,$$
$$\langle \pi^+\pi^0 \rangle = \langle 2, 1 \rangle .$$

(1)

In the SM, short-distance diagrams contribute only to the $\Delta I = 1/2$ and $\Delta I = 3/2$ transitions. Thus, the physical decay amplitudes are

$$A_{+-} \equiv \langle \pi^+\pi^- | T | B^0 \rangle = -\sqrt{\frac{1}{3}} A_{1/2} + \sqrt{\frac{1}{6}} A_{3/2} ,$$
$$A_{00} \equiv \langle \pi^0\pi^0 | T | B^0 \rangle = \sqrt{\frac{1}{6}} A_{1/2} + \sqrt{\frac{1}{3}} A_{3/2} ,$$
$$A_{+0} \equiv \langle \pi^+\pi^0 | T | B^+ \rangle = \frac{\sqrt{3}}{2} A_{3/2} ,$$

(2)

where $A_k$ ($k = 1/2, 3/2$) are the relevant reduced matrix elements. The parametrization for the CP-conjugate modes is similar, with the isospin amplitudes replaced by $\bar{A}_k$. Because there are two transitions, but three decays, the $B$ decay amplitudes obey a triangle relation:

$$\sqrt{2} A_{+0} = A_{+-} + \sqrt{2} A_{00} .$$

(3)

The measurement of the three decays allows one to extract $A_{3/2}$, while the CP-conjugate decays give $\bar{A}_{3/2}$. However, the penguin amplitude contributes only to $A_{1/2}$, so that the
relative phase between $A_{3/2}$ and $(q/p) \bar{A}_{3/2}$ is $2\alpha$, where $q/p$ describes $B$-$\bar{B}$ mixing. Thus, the penguin pollution has been removed.

Now, a generic $B \to \pi\pi$ transition contains $\Delta I = 1/2$, $\Delta I = 3/2$, and $\Delta I = 5/2$ terms, which contribute to the physical decay amplitudes as

$$
A_{+-} = -\sqrt{\frac{1}{3}} A_{1/2} + \sqrt{\frac{1}{6}} A_{3/2} - \sqrt{\frac{1}{6}} A_{5/2} ,
$$

$$
A_{00} = \sqrt{\frac{1}{6}} A_{1/2} + \sqrt{\frac{1}{3}} A_{3/2} - \sqrt{\frac{1}{3}} A_{5/2} ,
$$

$$
A_{+0} = \frac{\sqrt{3}}{2} A_{3/2} + \sqrt{\frac{1}{3}} A_{5/2} .
$$

(4)

The key point is that, in the presence of a nonzero $A_{5/2}$, the three $B \to \pi\pi$ amplitudes by themselves no longer obey a triangle relation. That relation is modified as follows:

$$
\sqrt{2} A_{+0} (1 - z) = A_{+-} + \sqrt{2} A_{00} ,
$$

(5)

with

$$
y \equiv \frac{A_{5/2}}{A_{3/2}} = \frac{z}{1 + \frac{2}{3} (1 - z)} .
$$

(6)

Although isospin symmetry was mentioned above, Eqs. (4) already take into account any possible isospin-breaking effects in the decay amplitudes, since the three isospin amplitudes are enough to encode all the information contained in the three experimental amplitudes.

Note also that, although $B \to \pi\pi$ decays were described above, the isospin analysis also holds for each final-state polarization of $B \to \rho\rho$ decays. In addition, it holds for the decay of any neutral isospin-1/2 meson. In particular, it applies if the initial meson is $K$ or $D$.

As noted above, the SM contributes only to the $\Delta I = 1/2$ and $\Delta I = 3/2$ transitions at short distance. The $\Delta I = 5/2$ transitions arise from rescattering effects, such as the combination of $A_{1/2}$ with a $\Delta I = 2$ electromagnetic rescattering of the two pions in the final state. This is naively estimated to be of order $|A_{5/2}| \sim \alpha|A_{1/2}|$, where $\alpha \sim 1/127$ is the electromagnetic coupling constant. There are also strong-interaction isospin-violating effects ($m_u \neq m_d$).

A $\Delta I = 5/2$ contribution was first identified in $K \to \pi\pi$ decays. In this case, $|A_{1/2}| \sim 20|A_{3/2}|$ (known as the $\Delta I = 1/2$ rule), meaning that $|A_{5/2}| \sim 0.1|A_{3/2}|$, thus influencing the decay $K^+ \to \pi^+ \pi^0$. A detailed comparison between theory and experiment is rather involved; a recent analysis within chiral perturbation theory may be found in Ref. [5].
In contrast, in the $B$ system it is expected that $|A_{1/2}| \sim |A_{3/2}|$ and $A_{5/2}$ is normally discarded (as above, in the isospin analysis). (Recent analyses including electromagnetic and strong isospin violation can be found in Ref. [6].) Our main purpose is to encourage experiments to scrutinize this assumption very closely, highlighting the fact that current data could be interpreted as showing some hints of $A_{5/2} \neq 0$. This is an important issue since, if $A_{5/2} \neq 0$, the isospin triangles do not close, and the extraction of $\alpha$ will be affected.

If the SM is valid and the arguments leading to $A_{5/2} = 0$ are correct, then four predictions can be made:

1. as noted above, the triangle in Eq. (3) and its conjugate version close.

2. all measurements of $\alpha$ will yield the same result. For example, the CP phase $\beta$ has already been measured very precisely in $B^0(t) \to J/\psi K_S$: $\sin 2\beta = 0.726 \pm 0.037$, which determines $\beta$ up to a four-fold ambiguity. The phase $\gamma$ can in principle be cleanly determined through CP violation in decays such as $B \to DK$ or from a fit to a variety of other measurements (the latest analysis gives $\gamma = 58.2^{+6.7}_{-5.4}$). The phase $\alpha$ is then given by $\alpha_{UT} \equiv \pi - \beta - \gamma$. If $A_{5/2} = 0$, then $\alpha_{fit} = \alpha_{UT}$, where $\alpha_{fit}$ is determined from $B \to \pi \pi$ or $B \to \rho \rho$ decays.

3. the direct CP asymmetry in $B^+ \to \pi^+\pi^0 (C+0)$ vanishes.

4. because there is one more observable than independent parameters in $B \to \pi \pi$, the interference CP asymmetry parameter in $B^0 \to \pi^0\pi^0 (S_{00})$, may be written as a function of the other observables: $F(S_{00}, C_{00}, B_{00}, S_{+-}, C_{+-}, B_{+-}, C_{+0}, B_{+0}) = 0$. Here $B$, $C$, and $S$ represent the CP-averaged branching ratio, the direct CP violation and the interference CP violation, respectively.

Of the four predictions, only the first and fourth are smoking-gun signals of $A_{5/2} \neq 0$; the others can be violated in the presence of physics beyond the SM with $A_{5/2} = 0$. The situation is summarized in Table I.

The most obvious test for a nonzero $A_{5/2}$ is the non-closure of the isospin triangle. In the following, we examine the present data on $B(\bar{B}) \to \pi \pi$ and $B(\bar{B}) \to \rho \rho$ decays with this in mind. In analyzing the $\rho \rho$ data we assume that these particles are completely longitudinally polarized. This is known experimentally to be an excellent approximation [10].
TABLE I: Strategies to utilize the experimental observables to distinguish three cases: neglecting isospin-violations in the SM (IC-SM); considering isospin-conserving new physics (NP); and considering $\Delta I = 5/2$ components.

|            | IC-SM | NP  | $\Delta I = 5/2$ |
|------------|-------|-----|------------------|
| triangle   | closes| closes| does not close   |
| $\alpha_{fit} - \alpha_{UT}$ | = 0   | $\neq 0$ | $\neq 0$        |
| $C_{+0}$   | = 0   | $\neq 0$ | $\neq 0$        |
| $F(S_{00}, \ldots)$ | = 0   | = 0   | $\neq 0$        |

Note that, since $A_{5/2}$ is expected to be small, it can only be seen in those triangles which are relatively flat. This is the case for the $B(\bar{B}) \to \rho\rho$ triangles, since the branching ratios for $B^0 \to \rho^0\rho^0$ and $\bar{B}^0 \to \rho^0\rho^0$ are much less than those of the other decay channels. It is also, by chance, the case for the $B \to \pi\pi$ triangle, but not for that of $\bar{B} \to \pi\pi$.

TABLE II: Branching ratios $B_f$, direct CP asymmetries $C_f$, and interference CP asymmetries $S_f$ (if applicable) for the three $B \to \pi\pi(\rho\rho)$ decay modes. Data comes from Refs. \[11, 12, 13, 14, 15, 16\]; averages (shown) are taken from Ref. \[17\].

|                   | $B_f[10^{-6}]$ | $C_f$       | $S_f$          |
|-------------------|----------------|-------------|----------------|
| $B^+ \to \pi^+\pi^0$ | $5.5 \pm 0.6$ | $-0.01 \pm 0.06$ |                 |
| $B^0 \to \pi^+\pi^-$ | $5.0 \pm 0.4$ | $-0.37 \pm 0.10$ | $-0.50 \pm 0.12$ |
| $B^0 \to \pi^0\pi^0$ | $1.45 \pm 0.29$ | $-0.28 \pm 0.40$ |                 |
| $B^+ \to \rho^+\rho^0$ | $26.4 \pm 6.4$ | $0.09 \pm 0.16$ |                 |
| $B^0 \to \rho^+\rho^-$ | $26.2 \pm 3.7$ | $-0.03 \pm 0.17$ | $-0.21 \pm 0.22$ |
| $B^0 \to \rho^0\rho^0$ | $\leq 1.1$ | $(-1, 1)$ |                 |

The current $B \to \pi\pi$ and $B \to \rho\rho$ experimental measurements are shown in Table II. This data can be turned into measurements of the $B \to f$ ($A_f$) and $\bar{B} \to f$ ($\bar{A}_f$) decay amplitudes through:

$$|A_f|^2 \propto B_f(1 + C_f) ,$$

$$|\bar{A}_f|^2 \propto B_f(1 - C_f) .$$  \(7\)
The proportionality constants involve two ingredients. First, there is the phase-space factor $K(m_B, m_f)$ which is essentially the same for all amplitudes in each channel. The second factor is the lifetime of the decaying $B$. Thus, $B_+$ and $B_-$ must be multiplied by $x = \tau(B^0)/\tau(B^\pm) = 1/x = 1.076 \pm 0.008$, due to the difference between the charged and neutral $B$ lifetimes [2]. We present the norms $|A_f|$ and $|\bar{A}_f|$ in Table III in arbitrary units (i.e. we include the factor $x$ but not $K(m_B, m_f)$).

| TABLE III: The isospin amplitudes in $B(\bar{B}) \to \pi\pi$ and $B(\bar{B}) \to \rho\rho$ (in arbitrary units). |
|--------------------------------------------------|
| $\sqrt{2}|A_{+0}|$ | $|A_{+-}|$ | $\sqrt{2}|A_{00}|$ |
| $B \to \pi\pi$: | 3.2 ± 0.3 | 1.8 ± 0.2 | 1.4 ± 0.6 |
| $B \to \rho\rho$: | 7.3 ± 1.5 | 5.0 ± 0.8 | $< 1.5\sqrt{1 + C_{00}^2}$ |
| $\sqrt{2}|\bar{A}_{+0}|$ | $|\bar{A}_{+-}|$ | $\sqrt{2}|\bar{A}_{00}|$ |
| $\bar{B} \to \pi\pi$: | 3.2 ± 0.3 | 2.6 ± 0.2 | 1.9 ± 0.5 |
| $\bar{B} \to \rho\rho$: | 6.7 ± 1.4 | 5.2 ± 0.8 | $< 1.5\sqrt{1 - C_{00}^2}$ |

We note in passing that, in addition, for the decays of the neutral $B$ mesons in which $S_f$ is measured, we also have access to the relative phase in

$$\lambda_f \equiv \frac{q}{p} \frac{\bar{A}_f}{A_f} = \frac{\pm \sqrt{1 - C_f^2 - S_f^2} + iS_f}{1 - C_f},$$

(8)

where $q/p$ arises from $B-\bar{B}$ mixing. However, we will not use this information.

In order to see if the isospin triangles close, we proceed as follows. In the absence of $A_{5/2}$, the triangle relation of Eq. (3) holds. We therefore have

$$|\sqrt{2}A_{+0}| = |A_{+-} + \sqrt{2}A_{00}| \leq |A_{+-}| + |\sqrt{2}A_{00}|.$$ (9)

Thus, if $|\sqrt{2}A_{+0}|$ is larger than $|A_{+-}| + |\sqrt{2}A_{00}|$, the triangle cannot close. The logic is similar for the CP-conjugate triangle.

For the $\pi\pi$ final state we see from the data that the central values do close both the $B \to \pi\pi$ and $\bar{B} \to \pi\pi$ unitarity triangles (but just barely for $B \to \pi\pi$): $|\sqrt{2}A_{+0}| = 3.2$, $|A_{+-}| + |\sqrt{2}A_{00}| = 3.2$; $|\sqrt{2}A_{+0}| = 3.2$, $|\bar{A}_{+-}| + |\sqrt{2}\bar{A}_{00}| = 4.5$.

However, the same is not true for $B \to \rho\rho$. Here, the data show that the $B(\bar{B}) \to \rho\rho$ isospin triangles do not close (we present a detailed analysis below). This is quite tantalizing:
is it simply a statistical flucturation, or is it a signal of a $\Delta I = 5/2$ component at a level larger than naive expectations?

Consider $B \to \rho \rho$. The length $\sqrt{2}|A_{00}|$ depends on the value of $C_{00}$, but for the purposes of illustration, suppose that $C_{00} = 0$. Then the central values give $|\sqrt{2}A_{+0}| = 7.3$, $|A_{+-}| + |\sqrt{2}A_{00}| < 6.5$, and the triangle does not close. This situation can be rectified by the inclusion of a $\Delta I = 5/2$ piece. For various values of $C_{00}$, the data require that

$$|y| = \left| \frac{A_{5/2}}{A_{3/2}} \right| \geq \begin{cases} 
0.01 \pm 0.19 ; & C_{00} = 1 \\
0.04 \pm 0.19 ; & C_{00} = 0.5 \\
0.07 \pm 0.19 ; & C_{00} = 0 \\
0.11 \pm 0.19 ; & C_{00} = -0.5 \\
0.21 \pm 0.19 ; & C_{00} = -1 
\end{cases}$$

(10)

For all values of $C_{00}$, a nonzero $A_{5/2}$ is required by the central values of the present data. However, a study of the errors shows that, at present, the effect is not yet statistically significant – it is at most at the level of $1\sigma$ ($C_{00} = -1$).

Turning to $\bar{B} \to \rho \rho$, the present data give

$$|\bar{y}| = \left| \frac{\bar{A}_{5/2}}{\bar{A}_{3/2}} \right| \geq \begin{cases} 
0.16 \pm 0.21 ; & C_{00} = 1 \\
0.06 \pm 0.21 ; & C_{00} = 0.5 \\
0.01 \pm 0.20 ; & C_{00} = 0 \\
\text{No Bound} ; & C_{00} = -0.5 \\
\text{No Bound} ; & C_{00} = -1 
\end{cases}$$

(11)

In this case, a nonzero value of $A_{5/2}$ is required only for certain values of $C_{00}$ (and the effect is not yet statistically significant).

This summarizes the present hint for a $\Delta I = 5/2$ piece in $B \to \rho \rho$ and $\bar{B} \to \rho \rho$ decays, separately. However, the signals go in opposite directions in each decay: the size of $A_{5/2}$ in $B \to \rho \rho$ decays increases as $C_{00}$ goes from $+1$ to $-1$, while $\bar{A}_{5/2}$ in $\bar{B} \to \rho \rho$ decays increases as $C_{00}$ goes from $-1$ to $+1$. As a result, we may combine information from both sets of data, using

$$|\sqrt{2}A_{+0}| + |\sqrt{2}\bar{A}_{+0}| \leq |A_{+-}| + |\bar{A}_{+-}| + |\sqrt{2}A_{00}| + |\sqrt{2}\bar{A}_{00}|.$$  

(12)

The presence of a $\Delta I = 5/2$ piece is implied if this inequality is not satisfied. The current
data imply that

\[
y \geq \begin{cases}
0.08 \pm 0.13 : & C_{00} = 1 \\
0.04 \pm 0.12 : & C_{00} = 0.5 \\
0.04 \pm 0.12 : & C_{00} = 0 \\
0.04 \pm 0.12 : & C_{00} = -0.5 \\
0.08 \pm 0.13 : & C_{00} = -1
\end{cases}
\]  \quad (13)

As above, the present data suggest a nonzero \( A_{5/2} \) piece for all values of \( C_{00} \), but the effect is not yet statistically significant.

In summary, we have shown that if the usual \( B(\bar{B}) \to \pi \pi \) or \( B(\bar{B}) \to \rho \rho \) isospin triangles do not close, this may be due to a SM \( \Delta I = \frac{5}{2} \) piece (\( A_{5/2} \)) at a level much larger than expected. This is a crucial question since a \( A_{5/2} \) piece can also mimic new-physics contributions to other observables, such as \( C_{+0} \) or \( \alpha_{\text{fit}} - \alpha_{UT} \) (see Table I). We have pointed out some strategies to disentangle \( A_{5/2} \) from legitimate new physics.

At present, data on \( B(\bar{B}) \to \rho \rho \) decays give a hint – not yet statistically significant – that the isospin triangles do not close. The purpose of this letter is to stress the need for experimental scrutiny of such a signal (and to continue to look for one in \( B(\bar{B}) \to \pi \pi \)). [A probe with \( F(S_{00}, \ldots) \) is also possible (Table I), particularly for \( B \to \rho \rho \), and advisable once the data become more precise.] If this signal remains, it may be a sign of a SM \( \Delta I = \frac{5}{2} \) piece.

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