Experimental status and prospects of the "$K\pi$ puzzle"

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We present a summary of the latest measurements of branching fractions and direct CP violations in the charmless hadronic two-body $B$ decays $B \rightarrow K^+\pi^-$, $K^+\pi^0$, $K^0\pi^+$ and $K^0\pi^0$, performed by the Belle, BABAR, CDF and CLEO experiments. The interpretations and the future prospects about discrepancies, called "$K\pi$ puzzle", between theoretical expectations and measurements are discussed.

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1 Introduction

Charmless hadronic two-body $B$ decays, $B \rightarrow K\pi$, provide opportunities to test the standard model (SM) and search for direct CP violation and new physics beyond the SM. $B$ mesons decay to $K\pi$ final states through several processes listed in Table 1. The tree and penguin processes dominantly contribute, and direct CP violation may arise from their interference. The partial rate CP violating asymmetry is measured as $A_{CP} = \frac{N(B) - N(B)}{N(B) + N(B)}$, where $N(B)$ is the yield for $B(B)$. By ignoring subdominant contributions and/or using isospin relations one can predict the branching fraction $\mathcal{B}$, $A_{CP}$, and these relations among the four $B \rightarrow K\pi$ decays and test the SM against the measurements. In this article we report on the $\mathcal{B}$ and $A_{CP}$ measurements by Belle, BABAR, CLEO and CDF, and discuss the discrepancies from the SM, called “$K\pi$ puzzle”, that have been found in the measurements, and the future prospects.

| Mode                  | Quark-level amplitude                  |
|-----------------------|----------------------------------------|
| $B^0 \rightarrow K^+\pi^-$ | $T + P + P_{EW}^C$                     |
| $B^+ \rightarrow K^+\pi^0$     | $T + P + C + P_{EW} + P_{EW}^C + A$    |
| $B^+ \rightarrow K^0\pi^+$     | $P + P_{EW}^C + A$                      |
| $B^0 \rightarrow K^0\pi^0$     | $P + C + P_{EW} + P_{EW}^C$             |

Table 1: Quark-level amplitudes for $B \rightarrow K\pi$. The contributed amplitudes are tree(T), penguin(P), colour-suppressed tree(C), electroweak penguin($P_{EW}$), colour-suppressed electroweak penguin($P_{EW}^C$), and weak annihilation(A).

2 Branching fractions

The branching fractions measured by Belle, BABAR and CLEO together with the averages of the three experiments are shown in Table 2. The results of three experiments are consistent with each other and agree with theoretical calculations in the SM. However, experimental results are all systematics dominated and therefore it is crucial to reduce the systematics for more stringent comparison with theory. Main systematics in Belle are due to charged track finding efficiency, kaon and pion identification, $K^0_S$ reconstruction, and $\pi^0$ reconstruction and similar limitations affect BABAR measurements.

The ratios of $\mathcal{B}$, defined as $R_c = 2\mathcal{B}(B^+ \rightarrow K^0\pi^+)/\mathcal{B}(B^+ \rightarrow K^+\pi^0)$ and $R_n = \mathcal{B}(B^0 \rightarrow K^+\pi^-)/2\mathcal{B}(B^0 \rightarrow K^0\pi^0)$, and the difference of the two ratios, $R_c - R_n$, are sensitive to new physics. In these ratios, there are advantages that some systematics can be reduced both in experimental measurements and theoretical calculations.
Ref. [10] predicts $R_c = 1.15 \pm 0.03$, $R_n = 1.12 \pm 0.03$ and $R_c - R_n = 0.03 \pm 0.04$. In 2003–2004, discrepancies of up to 2σ were found between measurements of $R_c - R_n$ and theory predictions, shown in Fig. 1. This "puzzle" gradually disappeared once more precise measurements shown reduced disagreement with theory.

![Figure 1](image)

Figure 1: $R_c - R_n$ measurements as a function of year. Blue hatched region represents ±1σ uncertainty of the SM expectation.

Current experimental results obtained from averages shown in Table 2 are $R_c = 1.12 \pm 0.07$, $R_n = 1.02 \pm 0.06$ and $R_c - R_n = 0.10 \pm 0.09$, which are in agreement with the calculations in the SM at the 1σ level.

### 3 Direct CP violation

Since both tree and penguin processes contribute to $B^0 \to K^+\pi^-$ and $B^+ \to K^+\pi^0$ decays, sizable $A_{CP}$ could be expected. Moreover, $A_{CP}$s in the $B^0 \to K^+\pi^-$ and $B^+ \to K^+\pi^0$ are expected to have approximately the same magnitude and sign [11]. On the other hand, both $B^+ \to K^0\pi^+$ and $B^0 \to K^0\pi^0$ are almost pure penguin processes, hence no sizable asymmetries are expected in the SM. The results of $A_{CP}$ measurements carried out by Belle, BABAR, CLEO, and CDF with the averages are shown in Table 3 [3, 4, 6, 8, 12–15]. All results are consistent across the four

|      | $B^0 \to K^+\pi^-$ | $B^+ \to K^+\pi^0$ | $B^+ \to K^0\pi^+$ | $B^0 \to K^0\pi^0$ |
|------|-------------------|-------------------|-------------------|-------------------|
| Belle| $19.9 \pm 0.4 \pm 0.8$ | $12.4 \pm 0.5 \pm 0.6$ | $22.8^{+0.8}_{-0.7} \pm 1.3$ | $8.7 \pm 0.5 \pm 0.6$ |
| BABAR| $19.1 \pm 0.6 \pm 0.6$ | $13.6 \pm 0.6 \pm 0.7$ | $23.9 \pm 1.1 \pm 1.0$ | $10.1 \pm 0.6 \pm 0.4$ |
| CLEO | $18.0^{+2.3+1.2}_{-2.1-0.9}$ | $12.9^{+2.4+1.2}_{-2.2-1.1}$ | $18.8^{+3.7+2.1}_{-3.3-1.8}$ | $12.8^{+4.0+1.7}_{-3.3-1.4}$ |
| Average | $19.4 \pm 0.6$ | $12.9 \pm 0.6$ | $23.1 \pm 1.0$ | $9.5 \pm 0.5$ |

Table 2: Summary of $B$ measurements performed by Belle, BABAR and CLEO.
1 fb

B modes, and although LHCb can improve Super $B$ isospin sum rule will be carried out by two super $A$ expected statistical error on the $A$ which is consistent with the measurement of $A$

explains the effect, this would indicate new physics beyond the SM [17 –19].

electric weak penguin contributions [17], or both [18]. If this effect were to be explained solely by enhancement of the colour-suppressed tree amplitude [16], electroweak penguin contributions [17], and both [18]. If this effect were to be explained solely by enhancement of the colour-suppressed tree amplitude its magnitude would have to be larger than [17,18] the tree amplitude. It means that the sizes of strong phases do not fit with factorization. If the electroweak penguin explains the effect, this would indicate new physics beyond the SM [17–19].

Table 3: Summary of $A_{CP}$ measurements by Belle, BABAR, CLEO and CDF.

|        | $B^0 \rightarrow K^+ \pi^-$ | $B^+ \rightarrow K^+ \pi^0$ | $B^+ \rightarrow K^0\pi^+$ | $B^0 \rightarrow K^0\pi^0$ |
|--------|------------------------------|-------------------------------|-----------------------------|-----------------------------|
| Belle  | $-0.094 \pm 0.018 \pm 0.008$ | +0.07 \pm 0.03 \pm 0.001 | +0.03 \pm 0.03 \pm 0.01 | +0.14 \pm 0.13 \pm 0.06 |
| BABAR  | $-0.107 \pm 0.016 \pm 0.004$ | +0.030 \pm 0.039 \pm 0.010 | -0.029 \pm 0.039 \pm 0.010 | -0.13 \pm 0.13 \pm 0.03 |
| CDF    | $-0.086 \pm 0.023 \pm 0.009$ | -                      | -                      | -                      |
| CLEO   | $-0.04 \pm 0.16 \pm 0.02$   | -0.29 \pm 0.23 \pm 0.02   | +0.18 \pm 0.24 \pm 0.02  | -                      |
| Average| $-0.098 \pm 0.012$          | +0.050 \pm 0.025          | +0.009 \pm 0.025         | -0.01 \pm 0.10          |

experiments. $A_{CP}(B^0 \rightarrow K^+ \pi^-)$ has reached 8σ significance, and $B^+ \rightarrow K^0\pi^+$ and $B^0 \rightarrow K^0\pi^0$ show no significant asymmetries, given the 3% and 10% uncertainties, respectively. These follow the expectations mentioned above. However, the measured $A_{CP}(B^+ \rightarrow K^0\pi^0)$ has a different magnitude and opposite sign to $A_{CP}(B^0 \rightarrow K^+\pi^-)$, and the difference is $\Delta A_{CP} = A_{CP}(B^+ \rightarrow K^+\pi^-) - A_{CP}(B^0 \rightarrow K^+\pi^-) = +0.148 \pm 0.028$, which is 5.3σ different from zero.

Unlike in the $B_0 \rightarrow K^+\pi^-$ decay, in addition to the tree and penguin, the colour-suppressed tree and electroweak penguin processes may contribute to $B^+ \rightarrow K^+\pi^0$ although these are expected to be much smaller than tree and penguin amplitudes.

There are several theoretical conjectures to try to explain this $\Delta A_{CP}$ puzzle with taking these contributions into account: enhancement of the colour-suppressed tree amplitude [16], electroweak penguin contributions [17], or both [18]. If this effect were to be explained solely by enhancement of the colour-suppressed tree amplitude its amplitude would have to be larger than [17–18] the tree amplitude. It means that the sizes of strong phases do not fit with factorization. If the electroweak penguin explains the effect, this would indicate new physics beyond the SM [17–19].

Further examination for new physics effect can be performed with isospin sum rule among four $A_{CP}$s [20]:

$$A_{CP}(B^0 \rightarrow K^+\pi^-) + A_{CP}(B^+ \rightarrow K^0\pi^+) \frac{\mathcal{B}(B^0 \rightarrow K^0\pi^0)}{\mathcal{B}(B^+ \rightarrow K^+\pi^-)} \frac{\tau_0}{\tau_+} =$$

$$A_{CP}(B^+ \rightarrow K^+\pi^0) \frac{2\mathcal{B}(B^+ \rightarrow K^+\pi^-)}{\mathcal{B}(B^0 \rightarrow K^+\pi^-)} \frac{\tau_0}{\tau_+} + A_{CP}(B^0 \rightarrow K^0\pi^0) \frac{2\mathcal{B}(B^0 \rightarrow K^0\pi^0)}{\mathcal{B}(B^0 \rightarrow K^+\pi^-)},$$

where $\tau_+(\tau_0)$ is a $B^+(B^0)$ meson lifetime. A violation of this sum rule would be an unambiguous evidence of new physics. With all of $\mathcal{B}$ and $A_{CP}$ results except for $A_{CP}(B^0 \rightarrow K^0\pi^0)$, the sum rule predicts $A_{CP}(B^0 \rightarrow K^0\pi^0)$ to be $-0.153 \pm 0.045$, which is consistent with the measurement of $A_{CP}(B^0 \rightarrow K^0\pi^0)$. More precise test of isospin sum rule will be carried out by two super $B$ factories, SuperKEKB [21] and SuperB [22], and LHCb [23]. The super $B$ factories will improve all of four $B \rightarrow K\pi$ modes, and although LHCb can improve $B^0 \rightarrow K^+\pi^-$ and $B^+ \rightarrow K^0\pi^+$ modes the expected statistical error on the $A_{CP}(B^+ \rightarrow K^+\pi^-)$ would reach the 0.5% level with 1 fb$^{-1}$. Fig 2 shows the expected error on the $A_{CP}(B^0 \rightarrow K^0\pi^0)$ measurement and
Figure 2: Expected $A_{CP}(B^0 \rightarrow K^0\pi^0)$ as a function of luminosity. Red solid line, dotted line, and solid curve show central value, systematic error, and 1σ error including systematics, respectively, of $A_{CP}(B^0 \rightarrow K^0\pi^0)$ based on current world average of $A_{CP}(B^0 \rightarrow K^0\pi^0)$. Blue line and curve represent central value and 1σ error including systematics predicted by isospin sum rule using current world averages except for $A_{CP}(B^0 \rightarrow K^0\pi^0)$. Dotted vertical line denotes current data set ($\sim 1$ ab$^{-1}$).

the prediction of isospin sum rule up to 20 ab$^{-1}$ based on current world averages by fixing present systematics, in case of the super $B$ factories. At 15 ab$^{-1}$, the error of $A_{CP}(B^0 \rightarrow K^0\pi^0)$ will reach the 5% level and the isospin sum rule will be violated with 3σ level if current central value of $A_{CP}(B^0 \rightarrow K^0\pi^0)$ would remain. However since the measurement will be systematics dominated, an effort to reduce the systematics becomes crucial.

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