IL NUOVO CIMENTO Vol. 32 C, N. 3-4 Maggio-Agosto 2009
DOI 10.1393/ncc/i2009-10423-7

Colloquia: IFAE 2009

Rare charmless B decays at the B-factories

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(ricevuto il 19 Settembre 2009; pubblicato online il 12 Ottobre 2009)

Summary. — We report on recent results on charmless hadronic and radiative rare B decays, based on data collected by the BaBar and Belle detectors at the B-factories. The potential reach of a Super B Factory is also presented.

PACS 12.15.Hh – Determination of Cabibbo-Kobayashi-Maskawa matrix elements.
PACS 13.20.He – Leptonic, semileptonic, and radiative decays of bottom mesons.
PACS 13.25.Hw – Hadronic decays of bottom mesons.

1. – Introduction

The study of rare B decays is a key ingredient for meeting two of the primary goals of the B-factories: assessing the validity of the Cabibbo-Kobayashi-Maskawa (CKM) picture of CP violation [1] by precisely measuring the elements of the Unitarity Triangle (UT), and searching for hints of New Physics (NP), or otherwise constraining NP scenarios, in processes which are suppressed in the Standard Model (SM). Effects induced at low energies by New Physics at some higher energy scale may eventually compete with SM contributions in processes which are prevented to occur at tree level, and might have a fair chance of being observed.

2. – Hadronic decays

2.1. *$B^+ \to \rho^+\rho^0$ and consequences on the CKM angle α.* – Branching fraction (BF) measurements for charmless hadronic B decays provide useful constraints to the model uncertainties in the extraction of the angles of the UT from time-dependent CP violation measurements. The most accurate determination of α comes from the isospin analysis on the $\rho\rho$ channels. Here, the model uncertainty on α introduced by penguin pollution is constrained geometrically by constructing two isospin triangles (one for B and one for $\bar{B}$) with the amplitudes of $\rho^+\rho^-$, $\rho^+\rho^0$, $\rho^0\rho^0$ processes [2]. An eight-fold ambiguity on α is intrinsic to this method. A great improvement in precision in the determination of α from $B \to \rho\rho$ has come from BaBar update of the BF measurement for $B^+ \to \rho^+\rho^0$ decay, using the full $424\,\mathrm{fb}^{-1}$ sample [3]. The

TABLE I. – *Branching fractions (and 90% CL UL) and polarizations for $B \to \omega X$ decays.*

Mode	S (σ)	$\mathcal{B}$ (10^{-6})	$\mathcal{B}$ UL (10^{-6})	f_L	A_{CP}
ωK^{*0}	4.1	$2.2 \pm 0.6 \pm 0.2$	–	$0.72 \pm 0.14 \pm 0.02$	$0.45 \pm 0.25 \pm 0.02$
ωK^{*+}	2.5	$2.4 \pm 1.0 \pm 0.2$	7.4	$0.41 \pm 0.18 \pm 0.05$	$0.29 \pm 0.35 \pm 0.02$
$\omega (K\pi)_0^{*0}$	9.8	$18.4 \pm 1.8 \pm 1.7$	–	–	$-0.07 \pm 0.09 \pm 0.02$
$\omega (K\pi)_0^{*+}$	9.2	$27.5 \pm 3.0 \pm 2.6$	–	–	$-0.10 \pm 0.09 \pm 0.02$
$\omega K_2^*(1430)^0$	5.0	$10.1 \pm 2.0 \pm 1.1$	–	$0.45 \pm 0.12 \pm 0.02$	$-0.37 \pm 0.17 \pm 0.02$
$\omega K_2^*(1430)^+$	6.1	$21.5 \pm 3.6 \pm 2.4$	–	$0.56 \pm 0.10 \pm 0.04$	$0.14 \pm 0.15 \pm 0.02$
$\omega \rho^0$	1.9	$0.8 \pm 0.5 \pm 0.2$	1.6	0.8 fixed	–
ωf_0	4.5	$1.0 \pm 0.3 \pm 0.1$	1.5	–	–
$\omega \rho^+$	9.8	$15.9 \pm 1.6 \pm 1.4$	–	$0.90 \pm 0.05 \pm 0.03$	$-0.20 \pm 0.09 \pm 0.02$

measured BF increased from $(18.2 \pm 3.0) \times 10^{-6}$ up to $(24.0 \pm 1.9) \times 10^{-6}$. The BF's of $B^+ \to \rho^+\rho^0$ and $B^0 \to \rho^+\rho^-$ are now very similar and much higher than that for the $B^0 \to \rho^0\rho^0$ penguin transition. As a consequence, the isospin triangles do not close, *i.e.* $|A^{+-}|/\sqrt{2} + |A^{00}| < |A^{+0}|$. This results in a degeneracy of the eight-fold ambiguity on α into a four-fold ambiguity, corresponding to peaks in the vicinity of 0°, 90° (two degenerate peaks), 180°. The precision on α is now at the level of 5%.

2˙2. *Search for $B^- \to K^+\pi^-\pi^-/K^-K^-\pi^+$ decays as a SM null test.* – In the SM, inclusive $b \to qq\bar{d}/qq\bar{s}$ transitions are expected to occur with BF's of $O(10^{-13})$ and $O(10^{-11})$, respectively [4, 5]. These processes are indeed suppressed by an additional CKM factor $|V_{td}V_{ts}^*| \approx 3 \times 10^{-4}$ with respect to $b \to q\bar{q}d/q\bar{q}s$ penguin transitions. For plausible values of the parameters in SM extensions, such as the minimal supersymmetric standard model with or without conserved R parity, two Higgs doublet models or models with extra $U(1)$ gauge bosons [4, 5], $qq\bar{d}/qq\bar{s}$ BF's may be comparable to the present experimental sensitivity. BaBar has searched for $B^- \to K^+\pi^-\pi^-/K^-K^-\pi^+$ with $(467 \pm 5) \times 10^{-6}$ $B\bar{B}$ pairs [6]. The resulting 90% confidence level (CL) upper limits (UL's) $\mathcal{B}(K^+\pi^-\pi^-) < 9.5 \times 10^{-7}$ and $\mathcal{B}(K^-K^-\pi^+) < 1.6 \times 10^{-7}$ supersede the previous measurements [7]. A sensitivity of $O(10^{-9})$ can be foreseen for a Super B Factory [8, 9], before systematics limit further improvements.

2˙3. *Branching fractions and polarizations for $B \to \omega K^*$, $\omega\rho$, ωf_0 decays.* – Naive estimates based on helicity and angular momentum conservation predict that vector-vector (VV) final states in B decays be almost fully longitudinally polarized ($f_L \approx 1$). Penguin-dominated decays seem however to have a smaller f_L. This so-called "polarization puzzle" [10] has been regarded until recently as a possible indication of NP. As of today, however, theoretical SM predictions taking into account non-factorizable contributions manage to reproduce the observed experimental pattern for BF's and polarizations, albeit with large uncertainties. BaBar has performed an angular analysis [11], measuring the BF's and polarizations for several $B \to \omega X$ VV transitions; decays to vector-tensor final states have also been investigated. Results are reported in table I and do not depart significatively from SM predictions. With the present level of theoretical uncertainties, this is not deemed a fruitful ground for NP searches, even at a Super B Factory.

3. – Radiative decays

3·1. *Fully inclusive* $B \to X_s\gamma$. – The inclusive measurement of the $B \to X_s\gamma$ BF represents one of the most powerful NP probes. The measurement of the photon momentum spectrum down to a photon energy as low as possible helps in constraining hadronic parameters which are key to a reliable measurement of V_{cb} and V_{ub} from $b \to c\ell\nu/u\ell\nu$.

Several approaches are possible, whose precision depends on the available statistics. At the B-factories, the most precise result has been reported by Belle [12] using an untagged analysis in the energy range $1.7 \leq E_\gamma^{\mathrm{c.m.s.}} \leq 2.8\,\mathrm{GeV}$, where subtraction of the continuum background and $B\bar{B}$ background relies on the off-resonance data sample and Monte Carlo samples tuned on data control samples, respectively. The measured BF is $\mathcal{B}(B \to X_s\gamma : E_\gamma^B > 1.7\,\mathrm{GeV}) = (3.31 \pm 0.19 \pm 0.37 \pm 0.01) \times 10^{-4}$, where the first error is statistical, the second systematic (dominated by uncertainties in the modeling of the $B\bar{B}$ background), and the third is due to the boost correction. Large theoretical uncertainties are introduced by the extrapolation from the lower cut on photon energy down to the value of 1.6 GeV used for theoretical predictions.

The most promising approaches at Super B luminosities make use of the analysis of the recoil system, which is tagged in either a hadronic or semileptonic B decay. Systematic uncertainties are expected to be reduced from the current 8% level to about 4%, which would result in a 3% precision on the combined BF [13].

3·2. *Isospin and* CP *asymmetries in* $B \to \rho\gamma$. – The study of exclusive radiative B decays, such as $B \to \rho\gamma$, may provide constraints on the CKM parameters and allow to search for physics beyond the SM. Compared to the inclusive channels, they are experimentally much cleaner, but theoretically more challenging, since large uncertainties arise when dependence on the external states is introduced.

Some cancellation of hadronic uncertainties is obtained in ratios of transition rates, such as (using charge-averaged rates) $R(\rho\gamma/K^*\gamma) \equiv \mathcal{B}(B \to \rho\gamma)/\mathcal{B}(B \to K^*\gamma)$, which can be used to constrain $|V_{td}/V_{ts}|$. BaBar [14] and Belle [15] have measured the values $R(\rho\gamma/K^*\gamma) = 0.042 \pm 0.009$ and $R(\rho\gamma/K^*\gamma) = 0.0302^{+0.0060+0.0026}_{-0.0055-0.0028}$, which result into values for $|V_{td}/V_{ts}|$ of $0.233^{+0.025+0.022}_{-0.024-0.021}$ and $0.195^{+0.020}_{-0.019} \pm 0.015$, respectively. These values are compatible with the measurement coming from B_s and B_d mixing. At a multi-ab^{-1} Super B Factory the experimental precision should reach about 3% [8], and the limiting factor would be the theoretical uncertainties due to $SU(3)$ breaking corrections, weak annihilation contributions to $B \to \rho\gamma$ (color allowed in charged B decays, while color suppressed in neutral B decays), and u-quark penguin amplitudes.

The sensitivity to NP can also be enhanced by studying measurable quantities which are as much as possible independent of non-perturbative QCD effects. Two such quantities are the CP and isospin asymmetries,

$$A^{\pm}_{CP} = \frac{\Gamma(B^- \to \rho^-\gamma) - \Gamma(B^+ \to \rho^+\gamma)}{\Gamma(B^- \to \rho^-\gamma) + \Gamma(B^+ \to \rho^+\gamma)}, \qquad \Delta(\rho\gamma) = \frac{\bar{\Gamma}(B^+ \to \rho^+\gamma)}{2\bar{\Gamma}(B^0 \to \rho^0\gamma)} - 1, \tag{1}$$

for which SM estimates are $A^{\pm}_{CP} = 0.10^{+0.03}_{-0.02}$ and $\Delta(\rho\gamma) = 0.04^{+0.14}_{-0.07}$ [16]. Belle [15] measured $A^{\pm}_{CP} = -0.11 \pm 0.32 \pm 0.09$, while for $\Delta(\rho\gamma)$ results are $-0.43^{+0.25}_{-0.22} \pm 0.10$ and $-0.48^{+0.21+0.08}_{-0.19-0.09}$ for BaBar [14] and Belle [15], respectively.

3·3. *Photon polarization in* $B^0 \to \rho K^0_S\gamma$. – In the SM, the chiral nature of weak interactions implies that the photon in $b \to q\gamma$ ($q = d, s$) be predominantly left-handed polarized, and that the right-handed ("wrong") polarization be suppressed by m_q/m_b. Similarly, $\bar{b} \to \bar{q}\gamma$ is predominantly right handed. The photon polarization can be measured from the time-dependent mixing-induced CP asymmetry in $B^0 \to f\gamma$ decay:

$$(2) \quad A_{CP}(t) = \frac{\Gamma(\bar{B}^0(t) \to f\gamma_{L+R}) - \Gamma(B^0(t) \to f\gamma_{L+R})}{\Gamma(\bar{B}^0(t) \to f\gamma_{L+R}) + \Gamma(B^0(t) \to f\gamma_{L+R})} = S_{f\gamma} \sin \Delta mt - C_{f\gamma} \cos \Delta mt,$$

which is also suppressed by m_q/m_b. $S_{f\gamma} = 0$ when the "wrong" photon polarization vanishes. The presence of NP may introduce new right-handed currents in the transition, and be signalled by a significant enhancement of $S_{f\gamma}$ above SM predictions [17]. Belle has recently measured the CP violation parameters in $B^0 \to K^0_S \rho^0 \gamma$ using 657 million $B\bar{B}$ pairs by performing a CP fit to $B^0 \to K^0_S \pi^+ \pi^- \gamma$ [18]. The resulting parameter $S_{\text{eff}} = 0.09 \pm 0.27(\text{stat.})^{+0.04}_{-0.07}(\text{syst.})$ is related to S for $K^0_S \rho^0 \gamma$ with a dilution factor $\mathcal{D} \equiv S_{\text{eff}}/S_{K^0_S \rho^0 \gamma} = 0.83^{+0.19}_{-0.03}$ that depends on the $K^{*\pm}\pi^{\mp}$ components. They thus obtain $S_{K^0_S \rho\gamma} = 0.11 \pm 0.33(\text{stat.})^{+0.05}_{-0.09}(\text{syst.})$, consistent with zero. With the data sample of a Super B Factory, such photon polarization measurements will be systematics-limited, and the precision of the test will be ultimately determined by SM expectations for these processes, which are below 5% [8] even including QCD corrections.

4. – Conclusions

Rare charmless B decays provide relevant information for over-constraining the CKM matrix and are a promising ground for NP searches at present B factories and at a future Super B Factory. An important "SM background" to NP searches is represented by non-perturbative QCD effects, which may produce significant deviations from the perturbative expectations and therefore should be properly understood and well under control before a clear sign of NP can be claimed.

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