POLARIZATION IN B DECAYS

Written March 2006 by A.V. Gritsan (Johns Hopkins University) and J.G. Smith (University of Colorado at Boulder)

We review the notation used in polarization measurements of B decays and discuss CP-violating observables in polarization measurements. We look at several examples of vector-vector B meson decays, while more details about the theory and experimental results in B decays can be found in a separate mini-review [1] in this *Review*.

The angular distribution of the B meson decay to two vector mesons with the sequential decay of each vector meson is of special interest because it reflects both weak- and strong-interaction dynamics. Using the helicity formalism [2], this distribution can be expressed as a function of three helicity angles which describe the flight direction of the vector meson daughters in the decay chain. An equivalent set of transversity angles can be used to reparameterize the angular distribution [3]. While the function of the angles depends on the quantum numbers of the vector mesons daughters, the differential decay width has three complex amplitudes A_λ corresponding to the vector meson helicity $\lambda = 0$ or ± 1 [4], where the last two can be expressed in terms of parity-even and parity-odd amplitudes $A_{\parallel,\perp} = (A_{+1} \pm A_{-1})/\sqrt{2}$. The angular distribution involves the terms proportional to the absolute values squared of the three amplitudes, plus the interference terms $\mathcal{I}m(A_\perp A_\parallel^*)$, $\mathcal{R}e(A_\parallel A_0^*)$, and $\mathcal{I}m(A_\perp A_0^*)$. Therefore, spin alignment in the vector-vector decay can be expressed with the parameters $f_L = |A_0|^2/\Sigma|A_\lambda|^2$, $f_\perp = |A_\perp|^2/\Sigma|A_\lambda|^2$, and the relative phases $\phi_\parallel = \arg(A_\parallel/A_0)$, $\phi_\perp = \arg(A_\perp/A_0)$.

Moreover, CP-violation can be tested in the angular distribution of the decay as the difference between the B and $\bar{B}$. This includes the vector triple-product asymmetries, direct-CP asymmetries in the amplitudes, and mixing-induced CP asymmetries in the time evolution. Overall, six non-trivial CP-violating parameters can be constructed from the $\bar{A}_\lambda$ and A_λ amplitudes [4]. Three parameters are equivalent to the three direct CP violating quantities, and in Ref. 5 they are chosen as the asymmetries in the overall decay rate $\mathcal{A}_{CP}$, in the f_L fraction $\mathcal{A}^0_{CP}$, and in the $f_\perp$ fraction $\mathcal{A}^\perp_{CP}$. Two other CP violating parameters are the weak phase differences:

$$\Delta\phi_\parallel = \frac{1}{2}\arg(\bar{A}_\parallel A_0/A_\parallel \bar{A}_0) \tag{1}$$

$$\Delta\phi_\perp = \frac{1}{2}\arg(\bar{A}_\perp A_0/A_\perp \bar{A}_0) - \frac{\pi}{2} \tag{2}$$

The $\frac{\pi}{2}$ term in Eq. (2) reflects the fact that $A_\perp$ and $\bar{A}_\perp$ differ in phase by π if CP is conserved. The two parameters $\Delta\phi_\parallel$ and $\Delta\phi_\perp$ are equivalent to triple-product asymmetries constructed from the vectors describing the decay angular distribution [4]. Finally, one CP-violating asymmetry is equivalent to the mixing-induced asymmetries studied in other decays [1].

B meson decays to heavy vector particles with charm, such as $B \to J/\psi K^*$, $D^*\rho$, D^*K^*, D^*D^*, $D^*D_s^*$, show substantial fraction of the amplitudes corresponding to transverse polarization of the vector mesons ($A_{\pm 1}$), in agreement with the factorization prediction. Most of these decays arise from tree-level $b \to c$ transitions and the amplitude hierarchy $|A_0| > |A_+| > |A_-|$ is expected from analyses based on quark-helicity conservation [6]. The larger the mass of the vector meson daughters, the weaker the inequality. The detailed amplitude analysis of the $B \to J/\psi K^*$ decays has been performed by the BABAR [7], Belle [8], CDF [9], and CLEO [10] collaborations. Most analyses are performed under the assumption of the absence of direct CP violation. The parameter values are given in the particle listing of this *Review*. The difference of the strong phases $\phi_\parallel$ and $\phi_\perp$ deviates significantly from zero. The most recent measurements [8] of CP-violating terms similar to those in $B \to \phi K^*$ [5] are consistent with zero.

In addition, the mixing-induced CP-violating asymmetry is measured in the CP-eigenstate mode $B^0 \to J/\psi K^{*0}$ [1,7,8]. This allows one to resolve the sign ambiguity of the $\cos 2\beta = \cos 2\phi_1$ term which appears in the time-dependent angular distribution due to interference of parity-even and parity-odd terms. This analysis relies on the knowledge of discrete ambiguities in the strong phases $\phi_\parallel$ and $\phi_\perp$ as discussed below. The BABAR experiment used a novel method based on the dependence on the $K\pi$ invariant mass of the interference between the S- and P-waves to resolve the discrete ambiguity in the determination of the strong phases $(\phi_{\parallel}, \phi_{\perp})$ in $B \to J/\psi K^*$ decays [7]. The result is in agreement with the amplitude hierarchy expectation [6]. The CDF [9] and D0 [11] experiments have studied the $B_s^0 \to J/\psi\phi$ decay and provided new lifetime measurements in addition to polarization results.

The interest in the polarization and CP asymmetry measurements in $B \to \phi K^*$ decays is mainly motivated by their potential sensitivity to physics beyond the Standard Model. In the Standard Model these decays are expected to arise only from the virtual loop effects in $b \to s$ penguin transitions. The amplitude hierarchy $|A_0| \gg |A_+| \gg |A_-|$ was expected in the B decays to light vector particles in penguin transitions [12,13] similarly to the tree-level transition analysis [6]. The decay amplitudes for $B \to \phi K^*$ have been measured by the BABAR and Belle experiments [5,14–16]. The fractions of longitudinal polarization $f_L = 0.50 \pm 0.07$ for the $B^+ \to \phi K^{*+}$ decay and $f_L = 0.48 \pm 0.04$ for the $B^0 \to \phi K^{*0}$ decay indicate significant departure from the naive expectation of predominant longitudinal polarization and suggests other contributions to the decay amplitude, previously neglected, either within or beyond the Standard Model [13,17]. The complete set of ten amplitude parameters measured in the $B^0 \to \phi K^{*0}$ decay are given in Table 1. Several other parameters could be constructed from the above ten parameters, as suggested in Ref. 18.

There is a discrete ambiguity in the phase $(\phi_{\parallel}, \phi_{\perp}, \Delta\phi_{\parallel}, \Delta\phi_{\perp})$ measurements and simple transformation of phases, for example, $(-\phi_{\parallel}, \pi - \phi_{\perp}, -\Delta\phi_{\parallel}, -\Delta\phi_{\perp})$, give rise to another set of values which produce the same angular distribution. The values closest to $(\pi,\ \pi,\ 0,\ 0)$ are given in Table 1, which is the preferred solution from s-quark helicity conservation [6,12,13]. However, this assumption is violated in the measurement of f_L and in the departure of $\phi_{\parallel}$ and $\phi_{\perp}$ from π, and needs experimental confirmation.

Like $B \to \phi K^*$, the decays $B \to \rho K^*$ and $B \to \omega K^*$ may be sensitive to New Physics. First measurements of the longitudinal polarization fraction in $B^+ \to \rho^0 K^{*+}$ [14] and

Table 1: Polarization and CP-violation parameters [5,16], along with the branching fraction $\mathcal{B}$ [5,15,19] measured in the $B^0 \to \phi K^{*0}$ decay.

parameter	average
$\mathcal{B}$	$(9.5 \pm 0.9) \times 10^{-6}$
f_L	0.48 ± 0.04
$f_\perp$	0.26 ± 0.05
$\phi_\parallel$	$2.36^{+0.18}_{-0.16}$
$\phi_\perp$	2.49 ± 0.18
A_{CP}	0.01 ± 0.07
A_{CP}^0	0.01 ± 0.09
$A_{CP}^\perp$	-0.16 ± 0.15
$\Delta\phi_\parallel$	0.02 ± 0.28
$\Delta\phi_\perp$	0.03 ± 0.33

$B^+ \to \rho^+ K^{*0}$ [20] have larger uncertainties due to lower yields and larger backgrounds. Only limits have been reported for the other $B \to \rho K^*$ and $B \to \omega K^*$ decays [21,22] and further improved measurements in all $B \to \rho K^*$ and $B \to \omega K^*$ decays are necessary to distinguish different interpretations [17].

The other class of vector-vector B meson decays is expected to arise from tree-level $b \to u$ transition. There is experimental confirmation of predominantly longitudinal polarization in the decays $B^0 \to \rho^+\rho^-$ [23], $B^+ \to \rho^0\rho^+$ [14,24], and $B^+ \to \omega\rho^+$ [21], which is consistent with the analysis of the quark helicity conservation [6]. Because the longitudinal amplitude dominates the decay, a detailed amplitude analysis is not possible with current B samples. Only limits have been set on the $B^0 \to \rho^0\rho^0$ [14,22,25] and $B^0 \to \omega\rho^0$ [21,26] decays, indicating that $b \to d$ penguin pollution is small in the charmless, strangeless vector-vector B decays.

In summary, there has been considerable recent interest in the polarization measurements of B meson decays because they reveal both weak- and strong-interaction dynamics [17,27]. New measurements will further elucidate the pattern of spin alignment measurements in rare B decays and further test the

Standard Model and strong interaction dynamics, including the non-factorizable contributions to the B decay amplitudes.

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