POLARIZATION STUDY IN B DECAYS TO VECTOR FINAL STATES

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The small longitudinal polarization fractions (50%) of $B \to \phi K^*$ measured by B factories contradict with the naive theoretical counting rules. We review the current theoretical status of the $B \to VV$ decay studies and calculate many of them in the perturbative QCD factorization approach based on $k_T$ factorization. We find that the penguin annihilation and non-factorizable emission diagrams can enhance the transverse polarization fractions. The PQCD results agree with experiments for the measured $B \to \phi K^*$, $B \to pK^*$ and $B \to \rho\rho$ channels, and we also predict new results (some different from other approaches) for those not yet measured channels.

1 Introduction

The abnormally large transverse momentum fraction measured by the B factories in the $B \to K^*\phi$ decays 1 arouse many discussions in the framework of standard model with hadronic uncertainties and also new physics contributions 2,3,4,5. Among these explanations some still face problem for explaining the identity fraction of the two transverse polarizations or the large relative strong phase between polarizations. In fact the perturbative QCD factorization approach (PQCD) based on $k_T$ factorization can really do a good job with 59% of the longitudinal polarization fraction and also the right ratio of the two transverse polarizations and right strong phase 6. The reason is that in the PQCD approach, a not very small space like penguin annihilation diagram contribute largely for the transverse polarizations. This annihilation type diagrams also contribute a large strong phase 7,8. Not surprisingly, the recent direct CP measurements of two B factories in $B^0 \to \pi^+\pi^-, \pi^-K^+$ decays also agree with the previous PQCD predictions 9.

Inspired by the successful achievement for the PQCD framework, we studied most of the charmless decays of B meson with two vector final states and also some $B_s$ decay channels. We find that longitudinal polarization fraction of those penguin dominant decays are indeed suppressed by the space like penguin diagrams due to (S-P)/(S+P) operators.

2 perturbative QCD approach formalism

In non-leptonic B decays, it is the heavy b quark decay through electroweak interaction, usually interchanging a W boson. By loop diagrams penguin operators are also involved, which together make the effective Hamiltonian for the weak decays:

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \left[ V_{ub} V_{us}^* (C_1 O_1^u + C_2 O_2^u) - V_{tb} V_{ts}^* \left( \sum_{i=3}^{10} C_i O_i + C_9 O_9 \right) \right] ,$$  (1)
where

\[
\begin{align*}
O_1^t &= s_\alpha \gamma^\mu Lu_\beta \cdot \bar{u}_\beta \gamma_\mu Lb_\alpha, \\
O_2^s &= \bar{s}_\alpha \gamma^\mu Lu_\alpha \cdot \bar{u}_\alpha \gamma_\mu Lb_\beta, \\
O_3 &= \bar{s}_\alpha \gamma^\mu Lb_\beta \cdot \sum q_q \bar{q}_\beta \gamma_\mu Lq_\beta, \\
O_4 &= \bar{s}_\alpha \gamma^\mu Lb_\beta \cdot \sum q_q \bar{q}_\beta \gamma_\mu Lq_\beta, \\
O_5 &= \bar{s}_\alpha \gamma^\mu Lb_\alpha \cdot \sum q_q \bar{q}_\beta \gamma_\mu Lq_\beta, \\
O_6 &= \bar{s}_\alpha \gamma^\mu Lb_\beta \cdot \sum q_q \bar{q}_\beta \gamma_\mu Lq_\beta, \\
O_7 &= \frac{3}{2} \bar{s}_\alpha \gamma^\mu Lb_\alpha \cdot \sum q_q e_q \bar{q}_\beta \gamma_\mu Lq_\beta, \\
O_8 &= \frac{3}{2} \bar{s}_\alpha \gamma^\mu Lb_\beta \cdot \sum q_q e_q \bar{q}_\beta \gamma_\mu Lq_\beta, \\
O_9 &= \frac{3}{2} \bar{s}_\alpha \gamma^\mu Lb_\alpha \cdot \sum q_q e_q \bar{q}_\beta \gamma_\mu Lq_\beta, \\
O_{10} &= \frac{3}{2} \bar{s}_\alpha \gamma^\mu Lb_\beta \cdot \sum q_q e_q \bar{q}_\beta \gamma_\mu Lq_\beta.
\end{align*}
\]

Here \(\alpha\) and \(\beta\) are the \(SU(3)\) color indices; \(L\) and \(R\) are the left- and right-handed projection operators with \(L = (1 - \gamma_5)\) and \(R = (1 + \gamma_5)\). The sum over \(q_q\) runs over the quark fields that are active at the scale \(\mu = O(m_b)\), i.e., \((q_q \epsilon\{u, d, s, c, b\})\). For \(b \to d\) transitions, one need only replace the \(s\) quark with \(d\) quark in eq. (2).

The effective four quark operators describe the hard electroweak process in b quark decays, however hadronization is needed for the meson decays. In hadronic B decays, more than one energy scale is involved, the factorization technique is very important here. Since all the decays are electro-weak decays, the electro-weak breaking scale 100GeV is involved. Unavoidably, the hadronization scale 200MeV is for the hadronic decays, which is non-perturbative. In the intermediate scale, the b quark mass is the energy release scale in these decays. Therefore a factorization theorem is required for the at least three energy scales.

For B meson decays with two light vector mesons in the final states, the light mesons obtain large momentum of 2.6GeV in the B meson rest frame. All the quarks inside the light mesons are therefore collinear like. Since the heavy b quark in B meson carry most of the energy of B meson, the light quark in B meson is soft. In the usual emission diagram of B decays, this quark goes to the final state meson without electroweak interaction with other quarks, which is called a spectator quark. Therefore there must be a connecting hard gluon to make it from soft like to collinear like. The hard part of the interaction becomes six quark operator rather than four. The soft dynamics here is factorized into the meson wave functions. The decay amplitude is infrared safe and can be factorized as the following formalism:

\[
C(t) \times H(t) \times \Phi(x) \times \exp \left[ -s(P, b) - 2 \int_{1/b}^{t} \frac{d\mu}{\mu} \gamma_q(\alpha_s(\mu)) \right],
\]

where \(C(t)\) are the corresponding Wilson coefficients of four quark operators, \(\Phi(x)\) are the meson wave functions and the variable \(t\) denotes the largest energy scale of hard process \(H\), which is the typical energy scale in PQCD approach and the Wilson coefficients are evolved to this scale. The exponential of \(S\) function is the so-called Sudakov form factor resulting from the resummation of double logarithms occurred in the QCD loop corrections, which can suppress the contribution from the non-perturbative region, making the perturbative region to give the dominant contribution. The “\(x\)” here denotes convolution, i.e., the integral on the momentum fractions and the transverse intervals of the corresponding mesons. Since logarithm corrections have been summed by renormalization group equations, the above factorization formula does not depend on the renormalization scale \(\mu\) explicitly.

3 \( B \to VV \) decays in the PQCD approach

In standard model, the four quark operators in eq. (2) is either \((V-A)\) or \((V+A)\), which implies that the emitted meson with left-handed quark and right-handed anti-quark or the inverse case. This spin structure is shown in Fig. 1(a). Therefore to make a longitudinal polarization meson costless, but require at least one quark spin flip to make a transverse polarized meson. Since the quark spin flip is suppressed in the heavy quark limit, the transverse polarization is suppressed in the charmless B meson decays. But for the space like penguin annihilation
diagrams with operator $O_6$, the situation shown in Fig. 1(b) is different [2]. This operator is $(V-A)(V+A)$ structure which becomes $(S+P)(S-P)$ after Fiertz transformation, shown in Fig. 1(c). In this case, the produced quark anti-quark pair going to different mesons contribute to the three polarizations almost equally, thus the transverse polarization gets twice contribution of longitudinal one. The annihilation contribution of operator $O_6$ is chirally enhanced in PQCD approach, therefore we can have a larger transverse contribution in penguin dominant decays like $B \to K^*\phi$ [6], while in QCD factorization approach, one has to increase the annihilation contribution by hand [2].

The input wave functions and various parameters are shown in the corresponding papers [10][11][12][13]. The numerical results for some of the $B \to K^*_\rho$, $\rho(\omega)\rho(\omega)$ decays are shown in Table 1 together with some of the experimental measurements [11][14]. From the table, one can see that the branching ratios calculated by PQCD approach agree well with the experiments. As for the measured polarization fractions most of them agree well except for $B^+ \to \rho^+ K^{*0}$, where there is a large discrepancy between the two experiments [11], our results agree with BABAR. The uncertainty showed in the table for $B \to \rho K^*$ decays are only from the change of $K^*$ wave functions, which shows high sensitivity of results with meson wave functions [10]. The tree dominant $B \to \rho^+\rho^-$, $\rho^+\rho^0$ and $\rho^+\omega$ decays are indeed longitudinal polarization dominant (with more than 90%). Meanwhile, the penguin dominant decays $B \to K^*\rho(\omega)$ have a reasonable transverse polarization fraction mainly due to a non-negligible annihilation diagram contribution.

Table 1: Branching ratios ($10^{-6}$) and polarization fractions using different type of light meson wave functions (the CKM phase angle $\phi_3$ is fixed as 60°)

| Decay       | Branching ratio | polarization fraction $R_L(\%)$ | theory | exp. | $R_\parallel(\%)$ | $R_\perp(\%)$ |
|-------------|-----------------|---------------------------------|--------|------|------------------|---------------|
| $B^0 \to \rho^- K^{*+}$ | 10-13           | $\leq 24$                      | 71 - 78 |      | 12               | 10            |
| $B^+ \to \rho^+ K^{*0}$ | 13-17           | $10.5 \pm 1.8$                 | 76 - 82 | 66 ± 7 | 13               | 10            |
| $B^+ \to \rho^0 K^{*+}$ | 6-9             | $10.6^{+3.8}_{-3.5}$           | 78 - 85 | 96$^{+4}_{-15}$ | 11              | 11            |
| $B^+ \to \omega K^{*+}$ | 5-8             | $<7.4$                         | 73 - 81 |      | 19               | 9             |
| $B^0 \to \rho^+ \rho^-$ | 35 ± 5          | 30 ± 6                         | 94     | 96$^{+7}_{-7}$ | 3                | 3             |
| $B^+ \to \rho^+ \rho^0$ | 17 ± 2 ± 1      | $26.4^{+6.4}_{-6.1}$           | 94     | 99 ± 5 | 4                | 2             |
| $B^+ \to \rho^+ \omega$ | 19 ± 2 ± 1      | $12.6^{+4.1}_{-3.8}$           | 97     | 88$^{+12}_{-15}$ | 1.5             | 1.5           |
| $B^0 \to \rho^0 \rho^0$ | 0.9 ± 0.1 ± 0.1 | $<1.1$                         | 60     |      | 22               | 18            |
| $B^0 \to \rho^0 \omega$ | 1.9 ± 0.2 ± 0.2 | $<3.3$                         | 87     |      | 6.5              | 6.5           |
| $B^0 \to \omega \omega$ | 1.2 ± 0.2 ± 0.2 | $<19$                          | 82     |      | 9                | 9             |

There are also time-like penguin contribution dominant decay channels such as $B^0 \to \phi\phi$, $B \to K^*K^*$ decays [15], etc. The perturbative QCD factorization approach calculation shows that reasonable transverse polarization fractions are about 30% in these decays. However, being CKM parameter $|V_{tb}V_{td}^*|$ suppressed, their branching ratios are $10^{-8} - 10^{-7}$, which are very
difficult to be measured. With the coming LHCb experiments, a large number of $B_s$ and $B_c$ mesons can be produced. We study the $B_s \to \rho K^{*}$ decays[15], with $B_s$ meson wave function constrained from other $B_s$ decays. The tree dominant mode $B_s \to \rho^+ K^{*-}$ is indeed longitudinal polarization dominant with more than 90%, while the color suppressed modes with only 40% longitudinal polarization. This is similar with the $B \to \rho \rho(\omega)$ case[11], which will provide a further test of the theory.

4 Summary

The polarization fractions measured by the two B factory experiments provide a test for various theories in the non-leptonic B decays. The perturbative QCD factorization approach based on $k_T$ factorization can explain the polarization fractions without new input parameters. The space like penguin annihilation diagrams, which is the main source of strong phase to explain the direct CP measurement of B decays, play an essential role in the enhancement of the transverse polarization fractions.

Acknowledgments

The author would like to thank Y. Li, Y.L. Shen, W. Wang and J. Zhu for contributions on works related here. This work was partly supported by the National Science Foundation of China.

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