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Getting Maximum Information From Incomplete Data on B $\rightarrow$ Charmomium-K_S Decays*

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Abstract

Tests of CP violation using B decays into CP eigenstates can be improved by using events normally rejected because of incomplete information. A search for lepton asymmetry in decays $\Upsilon(4S) \rightarrow B+\bar{B} \rightarrow (K_S+J/\psi)+(\text{lepton}^{\pm}+X)$ can be improved by including other $(c\bar{c})K_S$ events where the $(c\bar{c})$ pair is not bound in a J/ψ but in some other state like ψ' or η_c and where the lepton asymmetry is predicted to be the same as for $(K_S + J/\psi)$, other $(c\bar{c})K_S$ events which are not fully reconstructed and $(c\bar{c})K_L$ events where the K_L pair is not detected and which are predicted to have the opposite lepton asymmetry from corresponding K_S events. The information from these additional events can give improved statistics if suitable cuts can be found to improve signal/noise. The opposite asymmetry predicted for K_L events can test spurious lepton asymmetries due to systematic errors.

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DISCLAIMER

Introduction

At the present state of experimental information and theoretical understanding of CP violation, it is very important to search for some statistically significant experimental CP violation effect outside the kaon system. The B meson system offers the best opportunities for such a search. Since branching ratios and detection efficiencies for B decay modes of interest are very small, there is interest in getting the maximum information possible from events which cannot be fully reconstructed. The emphasis at the first stage should be on simply establishing the existence of a nonvanishing CP violation effect. Quantitative measurement of the relevant parameters can come later, after it is known that the effect exists.

So far the only clear experimental evidence for CP violation is in the parameter ϵ measured in the first CP experiment, and whose value has been subsequently determined with greater precision. The present experimental value of the parameter ϵ' is still consistent with zero and cannot distinguish between the zero predicted by superweak theory and the finite values predicted by the standard model with the Kobayashi-Maskawa mixing mechanism for CP violation. It should be noted that all the successes of the experimental predictions of the standard model are completely independent of CP and would be unaffected if the mixing matrix turns out to be real with a zero Kobayashi-Maskawa phase, and CP violation arises from a completely different mechanism. Thus there is no experimental reason at this time to believe that the KM explanation for CP violation is correct and experimental programs should keep in mind all other possibilities.

In discussing how to get more information from B decay data we consider as an example the case of a search for CP violation by measuring decays of both B mesons produced from the decay of the $\Upsilon(4S)$ and looking for a lepton asymmetry from one B decay and a CP eigenstate like ψK_S from the other.

$$\Upsilon(4S) \to B + \bar{B} \to (K_S + J/\psi) + (\text{lepton}^{\pm} + X) \tag{1}$$

The presently accepted technique of identifying fully reconstructed $J/\psi K_S$ decays via the leptonic decay of the J/ψ loses a factor of 7 in the leptonic branching ratio of the J/ψ and therefore about an order of magnitude when the detection efficiency is taken into account. We can gain a considerable factor in the lepton asymmetry signal if we can find ways to use:

1. Other $(c\bar{c})K_S$ events where the $(c\bar{c})$ pair is not bound in a J/ψ but in some other state like ψ' or η_c.

$$\Upsilon(4S) \to B + \bar{B} \to (K_S + c\bar{c} + (\text{lepton}^{\pm} + X) \tag{2a}$$

2. The other $(c\bar{c})K_S$ events which are not fully reconstructed,

$$\Upsilon(4S) \to B + \bar{B} \to (K_S + Y) + (\text{lepton}^{\pm} + X) \tag{2b}$$

3. $(c\bar{c})K_L$ events where the K_L pair is not detected.

$$\Upsilon(4S) \to B + \bar{B} \to (Y + J/\psi) + (\text{lepton}^{\pm} + X) \tag{2c}$$

All the $K_S(c\bar{c})_S$ and $K_L(c\bar{c})_S$ states are quasi-two-body and have a unique missing mass if only the K_S is detected and the charmonium is not fully reconstructed or if only the charmonium is detected and the kaon is lost, provided that the momentum of the initial decaying B is known. This gives a unique K_S momentum for each different charmonium bound state and one can examine the lepton asymmetry for all events containing a K_S with a momentum corresponding to the recoil against one of the charmonium S states. Similarly one can examine the lepton asymmetry for all events containing a reconstructed charmonium S state with a momentum corresponding to the recoil against a kaon. The selected momentum range can be enlarged to allow for the uncertainty in the initial B momentum.

The Use of Other Decay Modes

The same lepton asymmetry is predicted for all transitions (2a) where the J/ψ is replaced by any bound s-wave charmonium state. The conventional model for B decay into a kaon and a $(c\bar{c})$ pair produces the pair at a very short distance and therefore to a good approximation produces only bound states whose wave functions do not vanish at the origin; i.e. S states. The two possible quarkonium S states are the vector $^3S_1$ and the pseudoscalar ^1S_o states, which are respectively the J/ψ and the η_c and their radial excitations. All these states when produced with a K_S produce two-body final states $K_S(c\bar{c})_S$ which all have the same eigenvalue of CP; namely odd. This can be seen as follows: The K_S is even under CP, the J/ψ is even, the η_c is odd. The spin-zero B meson decay into two pseudoscalars is S-wave, while the decay into vector-pseudoscalar is P-wave. Thus we have

$$J/\psi^{(CP=+)} + K_S^{(CP=+)} + [P - wave]^{(P=CP=-)} \Rightarrow [J/\psi K_S]^{(CP=-)} \tag{3a}$$

$$\eta_c^{(CP=-)} + K_S^{(CP=+)} + [S - wave]^{(P=CP=+)} \Rightarrow [\eta_c K_S]^{(CP=-)} \quad (3b)$$

Thus the lepton asymmetry will be the same for all s-wave charmonium states produced with a K_S including all radial excitations. We will therefore enhance our CP-violation signal by including events with all these other states. However, these other states are not so easily detectable. We can enhance our ability to identify and use these other charmonium final states if we can develop methods to obtain information from events where the final states cannot be fully reconstructed.

We also note that the K_L has odd CP and all final states of the form $K_L(c\bar{c})_S$ will have even CP. Thus B decays produced together with these states from the $\Upsilon(4s)$ will have the opposite lepton asymmetry from those produced with $K_S(c\bar{c})_S$. So far the detectors used do not detect K_L, but here again this opposite asymmetry may be useful if we can develop methods to obtain information from events where the final states cannot be fully reconstructed. The possible use of regenerators enabling the detection of K_L might be considered in future detectors.

The Signal-Noise Problem

The feasibility of using inclusive events depends upon the possibility of obtaining a good signal to noise ratio. Looking at all the inclusive events with a K_S in the momentum ranges corresponding to desired decays enhances the signal, since it then includes all events otherwise lost because they cannot be fully reconstructed. It also increases the noise, because it includes many events with kaons in these momentum ranges from other decay modes. The question is whether the increase in noise can be controlled sufficiently by judicious cuts to eliminate background so that the overall effect is an improvement in signal to noise.

Let $N \pm \xi$ denote the numbers of events in a particular experiment observing the lepton asymmetry in the transition (1) in which the $\Upsilon(4S)$ decays into a B^o - $\bar{B}^o$ pair, one B decays into $J/\psi K_S$ and the other into a mode with a positive or a negative lepton respectively. The difference denoted by D_{exc} between the numbers of fully reconstructed exclusive events observed with positive and negative leptons is then given by[1]

$$D_{exc} = 2\eta \cdot BR \cdot \xi \pm \sqrt{2\eta \cdot BR \cdot N} = 2\eta \cdot BR \cdot \xi[1 \pm \sqrt{N/(2\eta \cdot BR \cdot \xi)}] \quad (4a)$$

where BR denotes the branching ratio to the observed final state and η the detection efficiency for this state. The fractional statistical error is therefore

$$\delta D_{exc} = \sqrt{N/(2\eta \cdot BR \cdot \xi)]} \tag{4b}$$

Counting all the events with a K_S in the momentum bin which contains all the $B^o \rightarrow J/\psi K_S$ decays has an efficiency is 100% for detecting these decays, but there is also a background denoted by B so that the number of events observed in the inclusive spectrum bin with positive and negative leptons is now $N + B \pm \xi$. For this case the difference denoted by D_{inc} between the numbers of inclusive events observed with positive and negative leptons is[1]

$$D_{inc} = 2\xi \pm \sqrt{2(N+B)} = 2\xi[1 \pm \sqrt{(N+B)/2\xi}] \tag{5a}$$

$$\delta D_{inc} = \sqrt{(N+B)/2\xi]} \tag{5b}$$

$$\frac{\delta D_{inc}}{\delta D_{exc}} = \frac{\sqrt{\eta \cdot BR}}{\sqrt{N/(N+B)}} \tag{5c}$$

The question is therefore which is greater, the detection efficiency × branching ratio $\eta \cdot BR$ in the conventional exclusive method or the signal to background ratio $\frac{N}{(N+B)}$ in the inclusive method. In the case where $\eta \cdot BR \approx 1/10$, a reasonable value for the detection of the J/ψ via the leptonic decay mode, the inclusive technique will be competitive even if the background is ten times bigger than the signal and therefore two orders of magnitude larger than the clean signal from fully reconstructed events. If we can further increase the signal by including the other charmonium decay modes we can tolerate a correspondingly greater background. It is therefore of interest to examine these possibilities and invesigate all possible cuts to reduce the background, with particular attention paid to the search for better cuts possible in future experiments with improved technologies. Combining the exclusive and inclusive data can give improved statistics as well as a consistency check.

In the case where a reconstructed charmonium S state is detected inclusively with a momentum corresponding to the recoil against a kaon there should be no overall asymmetry, since the K_S and K_L produce opposite asymmetries. Thus the asymmetry in those cases where the kaon is missed should exactly cancel the asymmetry observed in fully reconstructed events where both the charmonium and K_S are seen. The missed-kaon events will have lower signal to noise, since the asymmetry signals from missed K_S events will cancel the asymmetry signals from half of the K_L events if the detection efficiency for K_S is 50%. However, the asymmetry observed in missed kaon events can be used as a consistency check on systematics even if they do not appreciably improve statistics. Any systematic error giving rise to a spurious lepton asymmetry can be checked by the use of these events.

The signals from both observed K_S and missed-kaon events can be enhanced by 50% by the use of a detector which can see π^o's. The events with $K_S \to 2\pi^o$ decays will then add to the lepton asymmetry in the observed K_S events instead of subtracting from the opposite sign lepton asymmetry in missed-kaon events.

Cascade Decays

Additional information on incompletely reconstructed decays is available in events where a hadronic state X recoiling against a K_S decays into other hadrons,

$$B \to K_S + X \to K_S + A + Y \tag{6a}$$

where the hadronic state A is detected. but the states X and Y are not identified. Here there are two missing mass constraints for X and Y which can be used to reduce the background. Some examples are

$$B \to K_S + \psi' \to K_S + J/\psi + \pi^+ + \pi^- \tag{6b}$$

where the two pions are detected but the J/ψ is not reconstructed, and

$$B \to K_S + \psi'' \to K_S + D + \bar{D} \tag{6c}$$

where only one of the D mesons is reconstructed.

Note that both of these radially excited charmonium decay modes are interesting in their own right, and that the inclusive method may give useful information on their branching ratios before sufficient statistics is available from fully reconstructed events.

Time Resolution with Vertex Detectors in Asymmetric Colliders

In an asymmetric machine where vertex detectors can obtain time information the background due to charmed decays might be distinguished by this timing information. The background from incompletely reconstructed B-decay events can be classified into three different categories by using time information from vertex detectors sensitive to the lifetime of charmed particles which can distinguish between production and decay vertices of charmed mesons.

1. Prompt vertices. All the outgoing particles from a B decay will be observed to originate from a single vertex in events from decays of the form

$$B \rightarrow K_S + \text{hidden charm below } D\bar{D} \text{ threshold} \tag{7a}$$

2. Double vertices. The outgoing particles from a B decay will be observed to originate from two distinct vertices in events from decays of the form

$$B \rightarrow \text{naked charm} + X \rightarrow K_S + Y + X \quad . \tag{7b}$$

3. Triple vertices. The outgoing particles from a B decay will be observed to originate from three distinct vertices in events from decays of the form

$$B \rightarrow K_S + \psi'' \rightarrow K_S + D + \bar{D} \tag{7c}$$

This classification leads to two questions

1. Can rejection of delayed vertices improve the signal/noise for the use of $B \rightarrow K_S + X$ to get $B \rightarrow K_S + \text{hidden charm}$?
2. Can $B \rightarrow K_S + \psi''$ which is interesting in its own right be found by time resolution?

Conclusions - Possible Homework Suggestions

This suggests a homework program of examining the K_S spectrum from B decays in the momentum range where the K_S is recoiling against charmonium states and looking for ways to remove background events which are not from charmonium. Since the main background is expected to be from events where a charmed meson decays into a kaon which happens to be in this momentum range, it would be interesting to do a Monte Carlo study of such events to see whether there are any useful signatures present in the remaining hadrons recoiling against the K_S which could be used to identify them as background events and enable cuts in the data to be devised which would reduce the background due to charm decays. In particular, it would be interesting to determine which of the charm decay modes can produce a K_S which is accidentally in the momentum range investigated and to see whether any of these have clear signatures which can distinguish such events from K_S-charmonium decays even when they are not fully reconstructed.

Experimental data from charged B decays into charged kaons can be used to estimate branching ratios and background, since these are uniquely related to the neutral decays by isospin[2,3] and more charged decay data than neutral decay data may be available. Even rough estimates or upper limits on branching ratios of K_S - charmonium decays so far unobserved would be of interest. If in this way the branching ratios to other as yet unobserved charmonium decay modes can be estimated, additional information of physical interest not directly related to CP is obtained, since the relative branching ratios to different charmonium bound states is predicted by theoretical models. Possible decays into p-wave charmonium states should be investigated, since they can give rise to final states with opposite CP from those of the s-wave states. Although these p-wave states are not expected from the theoretical grounds discussed above, their absence should be confirmed experimentally.

Tests of systematic errors which can produce spurious lepton asymmetries should be investigated, in particular by the use of the K_L decay modes which produce opposite lepton asymmetry. Even though the K_L is not detected, any lepton asymmetry observed together with fully reconstructed K_S-charmonium events should cancel out in the inclusive events where the charmonium is fully reconstructed and has a momentum corresponding to a missing kaon. A spurious asymmetry should therefore show up as a failure of this cancellation. It may also be useful to think about detectors which can see K_L.

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