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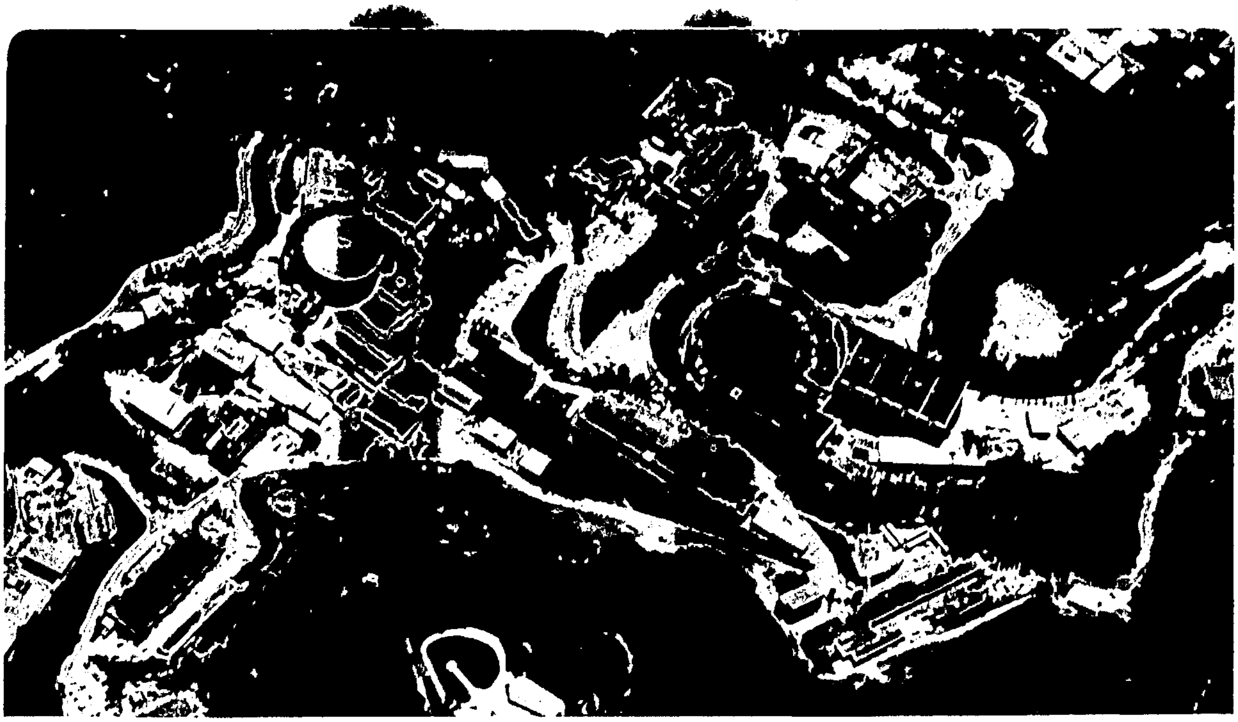

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I. General Introduction

It has been pointed out[1] that, with its high energy and luminosity, the SSC may provide the best or only way in which CP violation in heavy meson decays or the rare decay modes of such mesons can be observed. The major problem in the exploitation of the high rates of heavy quark production is the identification of interesting decays in the midst of a large background of more conventional processes. There have been some optimistic reports on the feasibility of such experiments,[2] but relatively little quantitative backup has been provided.

In the present report, we concentrate exclusively on B-meson decays. As is the case for K mesons, but not for charm or top decays, the favored modes are suppressed by the smallness of Cabibbo-Kobayashi-Maskawa angles, and therefore rare modes are relatively more frequent and potentially easier to observe.

Section II is theoretical. Part A gives a brief discussion of rare modes and part B provides a fairly detailed analysis of mixing and CP violation with particular emphasis on what can be measured. Section III discusses experimental issues, and Section IV gives a brief summary. Although the group listed above as authors participated in the discussions, the written material is largely due to G. Kane (Section II-A), M. Machacek (Section II-B), V. Luth and Jean Slaughter (Section III-A), F. Paige and G. Trilling (Sections III-B, C, D and IV). The brief discussion in III-E is based on work of J. Cronin which is described in more detail elsewhere in these proceedings.

II. Theoretical Considerations

A. Rare B Decays

There are three major categories of interesting decays; namely, (1) rare decays for which there is a standard model rate prediction, (2) decays forbidden by the standard model, and (3) decays which may allow the study of CP violation.

One should keep in mind that for all these classes of decays, effects much larger than those predicted by the Standard Model may enter. We briefly consider all of these categories in this section, and then provide in the next section a much more detailed discussion of CP violation phenomenology in B decay.

1. Rare Decays Allowed by the Standard Model.

a) $B_u \to \tau\nu$. This decay which proceeds via the annihilation diagram shown in Fig. 1a has a rate proportional to $f_B^2 |U_{bu}|^2$. The KM matrix element U_{bu} is known to be ≤ 0.006.[3] The branching ratio is less than 10^{-4}, and there is uncertainty in f_B and possible background at some level from $B_c \to \tau\nu$. However U_{bu} is a fundamental parameter, and only this method, and the study of B production at large X in $\bar{\nu}$ reactions, also difficult, are promising ways of measuring it.

b) $B \to K\ell^+\ell^-$, $K^*\ell^+\ell^-$. The relevant diagram, shown in Fig. 1b, is an important one-loop correction in the Standard Model. The branching ratio is estimated to be 10^{-5}.

c) $B \to \tau^+\tau^-$. This mode is analogous to $K_L \to \mu^+\mu^-$. Since the rate is proportional to M_ℓ^2, it is enhanced by a factor $(M_\ell/M_\mu)^2 \sim 300$, and the expected branching ratio is about 3×10^{-6}. The $\mu^+\mu^-$ and e^+e^- final states are expected with Standard Model branching ratios of 10^{-8} and 10^{-12} respectively.

2. Forbidden Decays. We can list decays which, while forbidden by the Standard Model, occur at interesting levels in some model which goes beyond. Detection of any of them would mean the discovery of a new effect not presently observed in nature. Examples of such decays include:

$B \to \mu e$, $\tau\mu$

$B \to \pi\mu e$, $\pi\tau\mu$, $K\mu e$, $K\tau\mu$

3. CP Violation in B Decay. To study CP violation, one can aim for several kinds of effects.

a) Search for like-sign dileptons as a signature of B°-$\bar{B}^\circ$ mixing, and compare $\ell^+\ell^+$ with $\ell^-\ell^-$ rates.

b) Study decays into exclusive modes to which both B° and $\bar{B}^\circ$ can decay. Examples are ψK_S, $\psi\phi$.

c) Within the Standard Model, one would expect equality of $(B \to D^+\ell^-\nu)$ and $(B \to D^-\ell^+\nu)$. However other ways of generating CP violation might lead to significant differences in these rates.

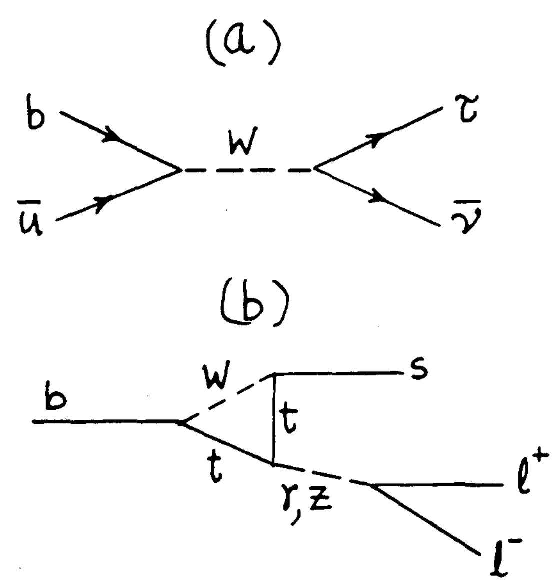

Fig. 1. Relevant diagrams for (a) $B \to \tau\nu$ and (b) $B \to K\ell^+\ell^-$ decay.

B. Theoretical Overview of Mixing and CP Violation in the $B\bar{B}$ System

1. Introduction. We review the definitions of basic parameters necessary for the description of mixing and CP violation for B mesons to establish our notation. We also review estimates of these parameters in the standard Kobayashi-Maskawa (KM) model which take account of recent mixing angle measurements based on $\frac{\Gamma(b \to u)}{\Gamma(b \to c)} < .05$ and the long B lifetime, $\tau_B \sim 10^{-12}$ sec. The standard model predictions provide a baseline for estimates of the size of mixing and CP violation effects in the $B\bar{B}$ system. We then discuss two experimental methods to search for these effects:

i) searches for like-sign dileptons from B meson semileptonic decays[4,5];

ii) searches for CP-violation effects through final-state interactions[5,6,7].

We pay particular attention to the time dependence of asymmetry parameters in ii) where the effects are expected to be largest.

In direct analogy with the K°-$\bar{K}^\circ$ mesons, the B°-$\bar{B}^\circ$ mesons produced in hadron collisions by strong interactions are not eigenstates of the full Hamiltonian H. For each B°-$\bar{B}^\circ$ meson type the CPT theorem and hermiticity restrict the form of the resulting matrix,

$$H\begin{pmatrix} B^\circ \\ \bar{B}^\circ \end{pmatrix} = \begin{pmatrix} M - i\frac{\Gamma}{2} & M_{12} - i\frac{\Gamma 12}{2} \\ M_{12}^{*} - i\frac{\Gamma 12}{2}^{*} & M - i\frac{\Gamma}{2} \end{pmatrix}\begin{pmatrix} B^\circ \\ \bar{B}^\circ \end{pmatrix} \quad (1)$$

In principle, diagrammatic and operator analyses may be used to calculate these matrix elements from the underlying theory.[4] Upon diagonalization of (1), the mass eigenstates B_1 (B_2) with masses m_1 (m_2) and decay rates Γ_1 (Γ_2), respectively, are mixtures of B° and $\bar{B}^\circ$ parametrized by

$$B_{1,2} = \frac{(1+\epsilon_B)B^\circ \pm (1-\epsilon_B)\bar{B}^\circ}{\sqrt{2(1+|\epsilon_B|^2)}} \quad (2)$$

where ϵ_B is the CP impurity parameter and

$$\frac{(1+\epsilon_B)}{(1-\epsilon_B)} = \frac{M_{12} - i\frac{\Gamma 12}{2}}{M_{12}^{*} - i\frac{\Gamma_{12}^{*}}{2}} \quad (3)$$

If we denote an initially (t=0) pure B° ($\bar{B}^\circ$) state which has evolved to some time t by $|B^\circ(t)\rangle$ ($|\bar{B}^\circ(t)\rangle$), respectively, then,

$$|B^\circ(t)\rangle = \frac{1}{2(1+\epsilon_B)}\Big\{(1+\epsilon_B)\Big[\exp\Big(-it(m_1 - i\frac{\Gamma 1}{2})\Big) + \exp\Big(-it(m_2 - i\frac{\Gamma 2}{2})\Big)\Big]|B^\circ\rangle + (1-\epsilon_B)\Big[\exp\Big(-it(m_1 - i\frac{\Gamma 1}{2})\Big) - \exp\Big(-it(m_2 - i\frac{\Gamma 2}{2})\Big)\Big]|\bar{B}^\circ\rangle\Big\} \quad (4a)$$

and

$$|\bar{B}^\circ(t)\rangle = \frac{1}{2(1-\epsilon_B)}\Big\{(1+\epsilon_B)\Big[\exp\Big(-it(m_1 - i\frac{\Gamma 1}{2})\Big) - \exp\Big(-it(m_2 - i\frac{\Gamma 2}{2})\Big)\Big]|B^\circ\rangle + (1-\epsilon_B)\Big[\exp\Big(-it(m_1 - i\frac{\Gamma 1}{2})\Big) + \exp\Big(-it(m_2 - i\frac{\Gamma 2}{2})\Big)\Big]|\bar{B}^\circ\rangle\Big\} \quad (4b)$$

Now define,

$$\Delta m \equiv m_1 - m_2 \ , \quad (5a)$$

$$m \equiv m_1 + m_2 \quad (5b)$$

$$\Delta\Gamma \equiv \Gamma_1 - \Gamma_2 \quad (5c)$$

and[8]

$$\Gamma \equiv \Gamma_1 + \Gamma_2 \quad . \quad (5d)$$

In the standard KM model[4,5,9] $\frac{\Delta\Gamma}{\Gamma} \sim \frac{1}{12}$ for the B_d-$\bar{B}_d$ system and $\frac{\Delta\Gamma}{\Gamma} \ll 1$ for the B_s-$\bar{B}_s$ system. Thus to good approximation these terms may be neglected and, in the following analysis, we assume $\frac{\Delta\Gamma}{\Gamma} \approx 0$. It is convenient to define mixing parameters x_d and x_s for the B_d and B_s neutral meson systems, respectively, where

$$x_j \equiv \frac{2(\Delta m)_j}{\Gamma_j} \qquad j = d,s \quad .$$

If all proper times are measured in units of the average B lifetime $2/\Gamma$, equations (4a-4b) take the simple form,

$$|B^\circ(t)\rangle = \exp\Big(\frac{-imt}{\Gamma} - \frac{t}{2}\Big)\Big\{\cos\Big(\frac{xt}{2}\Big)|B^\circ\rangle - i\frac{(1-\epsilon_B)}{(1+\epsilon_B)}\sin\Big(\frac{xt}{2}\Big)|\bar{B}^\circ\rangle\Big\} \quad (6a)$$

$$|\bar{B}^\circ(t)\rangle = \exp\Big(-\frac{imt}{\Gamma} - \frac{t}{2}\Big)\Big\{-i\frac{(1+\epsilon_B)}{(1-\epsilon_B)}\sin\Big(\frac{xt}{2}\Big)|B^\circ\rangle + \cos\Big(\frac{xt}{2}\Big)|\bar{B}^\circ\rangle\Big\} \quad (6b)$$

The mixing parameters x_d, x_s are strongly dependent on the evaluation of the hadronic matrix element. Estimates in the literature[6] yield $x_d \sim .14-.4$ and $x_s \sim .5-1$ where the larger mixing in each case is derived from the vacuum saturation approximation and the smaller mixing from the bag model hadronic wave functions.

2. Searches in Semileptonic B Meson Decays. One possible experimental means of probing the mixing and CP violation effects might be through a careful study of like-sign dileptons produced in semileptonic decays of $B\bar{B}$ pairs. Let N^{++}, N^{--}, N^{+-} and N^{-+} denote the numbers of events in which the B-$\bar{B}$ system decays into two leptons of the specified charges. Then,

$$r_2 \equiv \frac{N^{++} + N^{--}}{N^{++} + N^{--} + N^{+-} + N^{-+}} \quad (7)$$

describes the amount of mixing in the system,

$$a \equiv \frac{N^{++}-N^{--}}{N^{++}+N^{--}} \tag{8}$$

is a direct measure of CP violation in the system, (provided that the rates of $B_i\overline{B}_j$ and $\overline{B}_iB_j$ are exactly equal) and the overall lepton asymmetry

$$A \equiv \frac{N^{+}-N^{-}}{N^{+}+N^{-}} \quad , \tag{9}$$

with $N^{\pm}$ the total number of $\pm$ leptons, is a combination of both.[4] We expect b quarks to hadronize into $B_u(b\overline{u})$, $B_d(b\overline{d})$, and $B_s(b\overline{s})$ in the approximate ratio of 2:2:1. Thus equations (6) should be used to evaluate equations (7)-(9) separately for each possible meson pairing, $B_u\overline{B}_u$, $B_u\overline{B}_j$, $B_j\overline{B}_u$, $B_j\overline{B}_j$ j=s,d and $B_s\overline{B}_d \pm \overline{B}_sB_d$. The mixing and asymmetry parameters vanish for $B_u\overline{B}_u$ since non-neutral states do not mix. If the charge of the B meson can be determined, then the asymmetry parameters for the combined $B_u\overline{B}_j$ and $B_j\overline{B}_u$ systems are, to good approximation,

$$r_2 = \sin^2\left(\frac{x_j t}{2}\right) \quad , \tag{10a}$$

$$a = \frac{-4\mathrm{Re}\epsilon_B}{1+|\epsilon_B|^2} \quad , \tag{10b}$$

and

$$A = \frac{-4\mathrm{Re}\epsilon_B}{1+|\epsilon_B|^2}\sin^2\left(\frac{x_j t}{2}\right) \tag{10c}$$

where, in A, only leptons from B_j and $\overline{B}_j$ are included and t is the proper decay time (measured in units of average B° meson lifetime) of the neutral $\overline{B}_j(B_j)$ meson, and we have assumed equal production of $B_u\overline{B}_j$ and $\overline{B}_uB_j$. For standard model estimates of x_j, like-sign dilepton pairs will equal unlike-sign dilepton pairs in this system for t~4-11 lifetimes for j=d and t~1.5-3 lifetimes for j=s. The CP violation asymmetry a is, however, independent of time and directly proportional to $\mathrm{Re}\epsilon_B$. From equation (3) we see that $\mathrm{Re}\epsilon_B$ vanishes in the limit that M_{12} and Γ_{12} have equal phases. Indeed in the standard KM model calculation the leading contributions to M_{12} and Γ_{12} have the same phase. $\mathrm{Re}\epsilon_B$ is a higher order effect and thus small, 10^{-2}-10^{-3} for j=d and much smaller yet for j=s.[4] Thus even for optimal decay time, the total lepton charge asymmetry A is small. If only integrated rates are measured, the situation worsens

$$r_2 = \frac{x_j^2}{2(1+x_j^2)} \sim \begin{matrix} .01 - .07 & j = d \\ .1 - .25 & j = s \end{matrix} \tag{11a}$$

and

$$A = \frac{-2x_j^2\ \mathrm{Re}\epsilon_B}{(1+x_j^2)(1+|\epsilon_B|^2)} \lesssim 10^{-3} \tag{11b}$$

For completely neutral $B\overline{B}$ systems we have the added complication that the meson pairs are produced in coherent C-even or C-odd states depending on the production mechanism. Thus the state function at any time t is given by

$$|B_j(t),k;\overline{B}_{j'}(t),k'\rangle + (-1)^C\ |\overline{B}_j(t),k;B_{j'}(t),k'\rangle \tag{12}$$

For example, in the B_d-$\overline{B}_d$ meson system r_2 becomes

$$r_2 = \begin{cases} \sin^2(x_d\tau) & \text{C even} \\ \sin^2\left(x_d\dfrac{\Delta t}{2}\right) & \text{C odd} \end{cases} \tag{13a}$$

where $\tau = \frac{1}{2}(t_1+t_2)$ is the average decay time and $\Delta t = t_1-t_2$ is the difference in decay times for the meson pair. The parameter a is unchanged from the previous case and $A = ar_2$. When integrated over t_1 and t_2 we find

$$r_2 = \begin{cases} \dfrac{x_d^2}{2}\dfrac{3+x_d^2}{(1+x_d^2)^2} \sim .03-.19 & \text{C = even} \\ \dfrac{x_d^2}{2(1+x_d^2)} \sim .01-.07 & \text{C = odd} \end{cases} \tag{13b}$$

which is comparable to equation (11). Therefore, while mixing may be visible through detection of like-sign dileptons from B-$\overline{B}$ pairs, the observation of CP violation in this channel requires an experiment of great precision. This may prove particularly difficult in pp machines, such as the SSC, where an initial state charge asymmetry already exists.

3. Searches for CP violation in Nonleptonic final state interactions. A more promising method to study CP violation is to exploit such effects originating in B meson nonleptonic final states.[5,6] The basic idea is to pick a final state f common to both B° and $\overline{B}^\circ$ decays. Mixing causes the two amplitudes to interfere making the CP violation in the final state interaction observable. Some possible common final states f are

$$B_d\ (\overline{B}_d) \longrightarrow \begin{array}{l} \psi K_s \\ D^\circ(\overline{D}^\circ)\pi\text{'s} \longrightarrow K_s\pi\text{'s} \\ D\overline{D}K_s + \pi\text{'s} \\ F\overline{F}K_s + \pi\text{'s} \end{array}$$

and

$$B_s\ (\overline{B}_s) \longrightarrow \begin{array}{l} \psi\phi \\ \psi K\overline{K} \\ \psi F\overline{F} \end{array} \quad .$$

Although the following analysis applies to any such state f, we focus on the decay $B_d(\overline{B}_d) \to \psi K_s$ since this two-body mode permits a complete reconstruction of the final state. Following the notation of Bigi and Sanda[5] we may then define

$$M_f = \langle f|H|B_d^\circ\rangle$$

and

$$\overline{M}_f = \langle f|H|\overline{B}_d^\circ\rangle \quad .$$

For CP violation, $M_f \neq -\overline{M}_f$. The CP violation effect can be parametrized by a phase

$$\lambda \equiv \frac{M_f(1+\epsilon_B)}{\overline{M}_f(1-\epsilon_B)} \simeq -e^{-2i\phi}$$

with $|\lambda| \simeq 1$. In the standard KM model[6]

$$\sin \phi_d = \frac{S_3 \sin\delta}{\sqrt{S_3^2+S_2^2+2S_2S_3\cos\delta}}$$

and

$$\sin \phi_s \sim 0 + 0\left(\frac{m_c}{m_t}, S_2\right)$$

and

$$\text{Im}\,\lambda_j \sim \begin{cases} 0.3 & j = d \\ 0 & j = s \end{cases} .$$

As in section 2 we analyze each $B\overline{B}$ meson pair type independently. For $B_u\overline{B}_u$, there is obviously no mixing and thus no effect. For $B_j\overline{B}_u$ and $\overline{B}_jB_u$ the charge on $B_u(\overline{B}_u)$ prevents mixing with the neutral partner. Thus these pairs act like an incoherent source of B_j or $\overline{B}_j$, j=d,s. The charged mode is tagged by its semileptonic decay at time t_1. This identifies its partner as B_j or $\overline{B}_j$ at $t = 0$. This neutral partner decays to final state f at time t_2. If we define an asymmetry parameter

$$A_f \equiv \frac{\sigma(\ell^-,f)-\sigma(\ell^+,f)}{\sigma(\ell^-,f)+\sigma(\ell^+,f)} \tag{14}$$

and use equations (6) we find[6]

$$A_f = \text{Im}\lambda_j \sin(x_j t_2) \quad . \tag{15}$$

In Fig. 2, we show the dependence of $\sigma(\ell^-,f)$ and $\sigma(\ell^+,f)$ on time, for the value Imλ=0.3, x=0.4. The best signal to error ratio for the asymmetry (15) occurs at a time t which is the solution of the equation,

$$\tan xt = 2x.$$

For small x, $t\approx 2$, a time which is very comfortable from the point of view of vertex detection. If the decay time t_2 is integrated from a minimum value t_2° to ∞, the asymmetry parameter becomes

$$A_f = \frac{\text{Im}\lambda_j}{(1+x_j^2)}[x_j\cos(x_jt_2^\circ)+\sin(x_jt_2^\circ)]$$

$$\xrightarrow[t_2^\circ \to 0]{} \frac{x_j\text{Im}\lambda_j}{(1+x_j^2)} \tag{16}$$

Indeed, it will generally be necessary to keep t_1° and t_2°, the minimum allowable B meson decay times greater than zero by an amount determined by the detector spatial resolution to establish that B decay secondaries are being observed. In the KM model, the integrated asymmetry (j=d) ranges from

$$A_f \sim .03 - .06 \qquad \text{for} \quad \begin{matrix} t_2^\circ \sim 0 - 1 \\ x_d = .1 \end{matrix}$$

and

$$A_f \sim .1 - .2 \qquad \text{for} \quad \begin{matrix} t_2^\circ \sim 0 - 1 \\ x_d = .4 \end{matrix}$$

and is negligible for B_s.

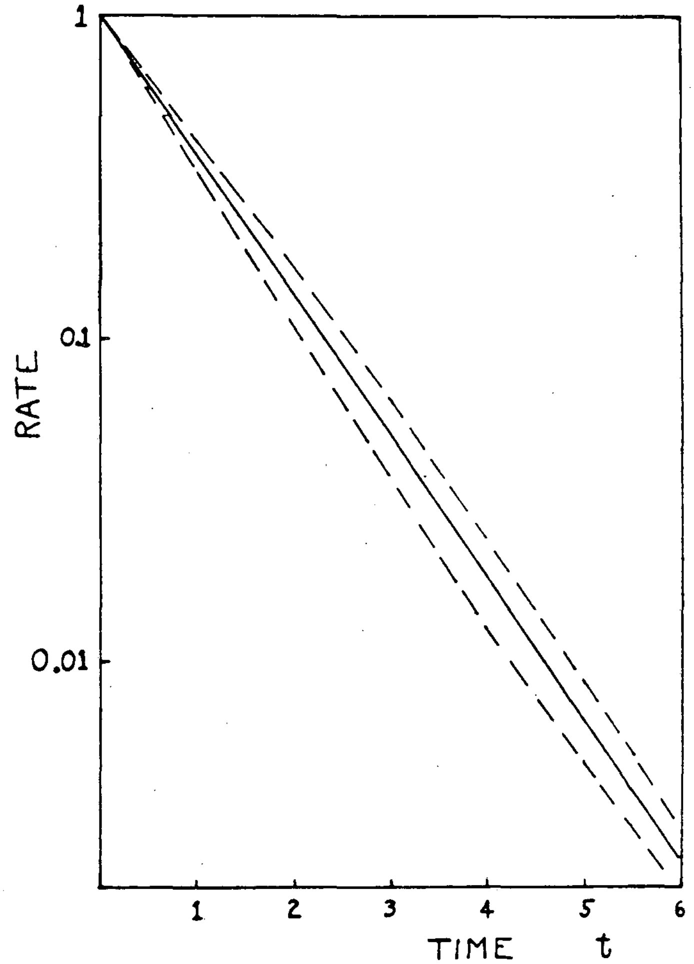

Fig. 2. Relative rates for $\sigma(\ell^-,f)$, $\sigma(\ell^+,f)$ for Imλ = 0.3, x = 0.4 (dashed) and Imλ = 0 (solid).

Neutral $B\overline{B}$ pairs must be treated as coherent states of definite C at production (see Eq. (12)). We assume equal efficiency to detect B or $\overline{B}$ for all momenta and drop the label k. We choose a semileptonic decay mode to tag the decaying particle as either a B° or $\overline{B}^\circ$ at time t_1. Then the complete time dependence of the state function of the other decaying meson is determined. The asymmetry parameters, defined in equation (14), for the $B_j\,\overline{B}_j$, become

$$A_f = \text{Im}\lambda_j \sin(x_j(t_1+t_2)) \quad \text{for} \quad C = \text{even} \tag{17a}$$

and

$$A_f = \text{Im}\lambda_j \sin(x_j(t_2-t_1)) \quad \text{for} \quad C = \text{odd}. \tag{17b}$$

After integrating over the poorly determined semileptonic decay time from t_1° to ∞, the asymmetries are,

$$A_f = \frac{\text{Im}\lambda_j}{(1+x_j^2)}[x_j\cos(x_j(t_1^\circ+t_2))+\sin(x_j(t_1^\circ+t_2))] \tag{18a}$$

for C even, and

$$A_f = \frac{\text{Im}\lambda_j}{(1+x_j^2)}[\sin(x_j(t_2-t_1^\circ))-x_j\cos(x_j(t_2-t_1^\circ))] \tag{18b}$$

for C odd.

Again integrating from t_2° to ∞, we find

$$A_f = \mathrm{Im}\lambda_j \left[\frac{2x_j}{(1+x_j^2)^2}\cos(x_j(t_1^\circ+t_2^\circ)) + \frac{(1-x_j^2)}{(1+x_j^2)^2}\sin(x_j(t_1^\circ+t_2^\circ)) \right]$$

$$\xrightarrow[t_1^\circ, t_2^\circ \to 0]{} \frac{2\,\mathrm{Im}\lambda_j x_j}{(1+x_j^2)^2} \qquad \text{for C even,} \tag{19a}$$

and

$$A_f = \mathrm{Im}\lambda_j \sin(x_j(t_2^\circ - t_1^\circ))$$

$$\xrightarrow[t_1^\circ, t_2^\circ \to 0]{} 0 \qquad \text{for C odd.} \tag{19b}$$

Representative values of the integrated asymmetries in the KM model for x_d=.1 and .4 and for various values of t_1°, t_2° are listed in Table I.

Table I: Integrated Asymmetry Parameters A_f for the $B_d\bar{B}_d$ System

t_1°	t_2°	C even (x=.1)	C odd (x=.1)	C even (x=.4)	C odd (x=.4)
0	0	0.06	0	0.08	0
0.5	0.5	0.09	0	0.24	0
1	0.5	0.10	-0.015	0.25	-0.06
0.5	1	0.10	0.015	0.25	0.06
1	1	0.12	0	0.26	0

The treatment of the asymmetry parameter for the remaining neutral pairs, $B_s\bar{B}_d+(-1)^C B_d\bar{B}_s$, is similar to that for $B_j\bar{B}_j$ except that two different sets of mixing parameters are involved. We assume that B_s and $\bar{B}_s$ decay into f are suppressed to a negligible level. The asymmetry parameters are then

$$A_f = \mathrm{Im}\lambda_d \sin(x_d t_2 + x_s t_1) \qquad \text{for C even} \tag{20a}$$

and

$$A_f = \mathrm{Im}\lambda_d \sin(x_d t_2 - x_s t_1) \qquad \text{for C odd.} \tag{20b}$$

Again integrating from t_1° over the lepton decay times

$$A_f = \frac{\mathrm{Im}\lambda_d}{1+x_s^2}\left[x_s\cos(x_s t_1^\circ + x_d t_2) + \sin(x_d t_2 + x_s t_1^\circ)\right] \tag{21a}$$

for C even,

$$A_f = \frac{\mathrm{Im}\lambda_d}{1+x_s^2}\left[-x_s\cos(x_d t_2 - x_s t_1^\circ) + \sin(x_d t_2 - x_s t_1^\circ)\right] \tag{21b}$$

for C odd.

Finally integrating over t_2 from t_2° to infinity we complete this set of time-dependent asymmetry parameters with

$$A_f = \frac{\mathrm{Im}\lambda_d}{(1+x_s^2)(1+x_d^2)}\left[(x_s+x_d)\cos(x_s t_1^\circ + x_d t_2^\circ) + (1-x_s x_d)\sin(x_s t_1^\circ + x_d t_2^\circ)\right]$$

$$\xrightarrow[t_1^\circ, t_2^\circ \to 0]{} \frac{\mathrm{Im}\lambda_d (x_s+x_d)}{(1+x_s^2)(1+x_d^2)} \tag{22a}$$

for C even, and

$$A_f = \frac{\mathrm{Im}\lambda_d}{(1+x_s^2)(1+x_d^2)}\left[(-x_s+x_d)\cos(x_d t_2^\circ - x_s t_1^\circ) + (1+x_s x_d)\sin(x_d t_2^\circ - x_s t_1^\circ)\right]$$

$$\xrightarrow[t_1^\circ, t_2^\circ \to 0]{} \frac{\mathrm{Im}\lambda_d\,[-x_s+x_d]}{(1+x_s^2)(1+x_d^2)}, \tag{22b}$$

for C odd. Representative values are listed in Table II.

Table II: Integrated Asymmetry Parameters A_f for the $B_s\bar{B}_d+(-1)^C B_d\bar{B}_s$ System

t_1°	t_2°	C even x_d=.1 x_s=.5	C odd x_d=.1 x_s=.5	C even x_d=.4 x_s=1	C odd x_d=.4 x_s=1
0	0	0.142	-.095	0.181	-0.078
0.5	0.5	0.203	-.143	0.188	-0.128
1	0.5	0.240	-.194	0.138	-0.184
0.5	1	0.211	-.131	0.173	-0.095
1	1	0.118	-.184	0.107	-0.166

In all of the above calculations we have assumed that the different B meson types are experimentally distinguishable. In practice this may be difficult. We therefore calculate an average CP violating asymmetry A_f where each asymmetry A_f is weighted by the fraction of the relative production of a given meson pair type. We assume that C even and C odd states are equally likely and that hadronization with u, d and s quarks is in the ratio 2:2:1. From equations (15), (18), and (21) we find (integrating over t_1)

$$A_f = \mathrm{Im}\lambda_d \left[\frac{1}{2}\sin(x_d t_2) + \frac{[x_d \cos(x_d(t_1^\circ + t_2))] + \sin(x_d(t_1^\circ + t_2))}{8\,(1+x_d^2)} \right.$$

$$+ \frac{[\sin(x_d(t_2 - t_1^\circ)) - x_d \cos\,(x_d(t_2 - t_1^\circ))]}{8\,(1+x_d^2)}$$

$$+ \frac{[x_s \cos(x_s t_1^\circ + x_d t_2) + \sin\,(x_d t_2 + x_s t_1^\circ)]}{8\,(1+x_s^2)}$$

$$+ \frac{[-x_s \cos(x_d t_2 - x_s t_1^\circ) + \sin(x_d t_2 - x_s t_1^\circ)]}{8\,(1+x_s^2)} \qquad (23)$$

When $t_1^\circ = 0$, equation (23) takes the simple form

$$A_f = \frac{\mathrm{Im}\lambda_d \sin(x_d t_2)[2(1+x_d^2)(1+x_s^2)+(1+x_s^2)+(1+x_d^2)]}{4\,(1+x_d^2)(1+x_s^2)} \qquad (24)$$

Equation (24) has the same shape as the asymmetry depicted in Fig. 2, with an amplitude reduced by about a factor of 2. There is relatively little dependence of A_f on t_1° since the $B_u\bar{B}_d$, $\bar{B}_u B_d$ contributions dominate the asymmetry. From (24), using $\mathrm{Im}\lambda_d \sim 0.3$, and two choices of x_d and x_s, we obtain the following estimates for A_f:

$A_f = 0.28 \sin x_d t_2 = .028$ at $t_2 = 1$ lifetime
for $x_d = 0.1$, $x_s = 0.5$ and,
$A_f = 0.25 \sin x_d t_2 = .098$ at $t_2 = 1$ lifetime
for $x_d = 0.4$, $x_s = 1$.

Finally the average integrated CP violation asymmetry for $f = \psi K_s$ can be found in the same way as equation (23) from equations (16), (19), and (22). Representing roughly the effect of a vertex detector by taking $t_1^\circ = t_2^\circ = 1$, we find that averaging reduces the integrated asymmetry by a factor of ~2. Thus for values of the mixing x_d, x_s and CP violation $\mathrm{Im}\lambda_d$ expected by the standard KM model, the integrated asymmetry averaged over all possible B meson pairings is

$$A_f \Big|_{t_1^\circ = t_2^\circ = 1} \approx 4\text{-}12\% \quad .$$

4. Concluding Remarks. In conclusion, we note the following:

a) The CP violating effects that we have discussed all require that both B and $\bar{B}$ decays from the same production event be detected.

b) We have assumed exact equality of $\bar{B}_i B_j$ and $B_i \bar{B}_j$ production. This is undoubtedly violated at some level in an initial PP state although the dominant production from gluon-gluon collisions would lead to the above equality. For very small effects such as expected dilepton asymmetries the issue of how well the above assumption is fulfilled may become important.

c) All the CP violating effects discussed in this section require both significant mixing ($x \neq 0$) and CP violation ($\mathrm{Re}\,\varepsilon_B \neq 0$ or $\mathrm{Im}\lambda \neq 0$). The estimates given are based on the KM model of CP violation. If there are other sources of CP violation, much larger effects could arise.

IV. Experimental Considerations

A. Efficacy of Various Sources

In Table III, we give a rough comparison of expected total rates and $B\bar{B}$ rates from various accelerator and storage ring facilities. The quantity f_B is the estimated fraction of the total cross section leading to $B\bar{B}$ pairs. The assumed collider luminosities are 10^{30} (TeVI), 10^{32} (SSC) and 10^{31} (Lep/SLC) all in $cm^{-2}\ sec^{-1}$. For the fixed target experiments, the total rates have been fixed at 10^7Hz, which appears to be a reasonable maximum for the relatively complex experiments with vertex detectors required for the study of B physics. The $B\bar{B}$ cross sections are of course only rough estimates. It is clear from Table III that the SSC collider enjoys a large advantage for both rate and signal to background relative to other hadron sources. Lep/SLC have an enormous signal to background advantage over all hadron machines, but the rates are relatively low.

With respect to the SSC, these calculations suggest an a-priori two-order-of-magnitude advantage for operation in the collider mode as opposed to the fixed target mode. It is conceivable that the acceptance in a fixed-target experiment can be better for less cost, but it seems doubtful that the two orders of magnitude can be regained. For this reason, we have chosen to emphasize experiments in the SSC collider mode.

Table III. Produced $B\bar{B}$ Rates from Various Sources

Source	Energy (GeV)	σ (mb)	Total Interaction Rate (Hz)	f_B	$B\bar{B}$ in 10^7 sec
TeV II fixed target	45	50	10^7	10^{-6}	10^8
SSC fixed target	200	80	10^7	10^{-5}	10^9
TeV I $\bar{P}P$ Collider	2000	100	10^5	10^{-4}	10^8
SSC PP Collider	40000	200	10^7	10^{-3}	10^{11}
LEP/SLC e^+e^- Collider	92	3×10^{-5}	0.3	0.14	4×10^5

B. Some General Rate Considerations

We consider $B\bar{B}$ production by the collider in the central region which we define as the angular interval about the beam line,

$$30^\circ \leq \theta \leq 150^\circ \quad .$$

We assume the existence of a detector which covers this polar angle range and the full azimuth, and idealize the luminous region as a line source of transverse width, $\sigma = 7\ \mu m$ and length a few cm.

We base our cross section information on the ISAJET program.[10] Since the relevant x values for $B\bar{B}$ production are extremely small at 40 TeV, the theoretical predictions are very uncertain. However, the numbers seem plausible, and we use them.

The overall $B\bar{B}$ cross section at 40 TeV is estimated to be about 220 μb. To provide a first level trigger, and to have B mesons which are not too soft (we have to detect their finite flight paths in a vertex detector), we require the transverse momentum of each B-jet to be greater than 10 GeV/c. Some relevant cross sections and multiplicities are given in Table IV. For the purposes of the discussion, we have treated D mesons as having zero lifetime, and given in Table IV only the stable charged multiplicity. It is clear from Table IV that the angular and p_T cuts already reduce the effective cross section by a factor of 200.

We now consider the problem of B recognition through use of a high resolution vertex detector. The actual reconstruction of separated vertices in a multihadron environment is an extremely difficult problem compounded in the case of B decay by the fact that usually out of a total average of 5 charged secondaries, half go with the B vertex and the other half with a separate D vertex. However, a more straightforward procedure is the observation of finite impact parameters for decay tracks with respect to the beam line. The distribution of impact parameters is very broad with a mean value of the order of cτ. Impact parameter distributions from B decay secondaries, for B jets with p_T>10 GeV/c, are given in Table V. A B lifetime of 10^{-12} sec has been assumed. In Table V(a), the distribution of impact parameters, with a 24% probability for values less than 20 μm, shows the large width. The median value is 80 μm.

More useful perhaps is the distribution of the ratio of impact parameters to error in impact parameter. This error can be written in the form,

Table IV: $B\bar{B}$ Cross Sections and Multiplicities

Total	220 μb
Two B jets both with p_T > 10 GeV/c	30 μb[(a)]
Plus $\lvert y_{jet}\rvert$ < 1.5 on both jets	5.4 μb
Two B jets with p_T > 15 GeV/c	11 μb[(a)]
Plus $\lvert y_{jet}\rvert$ < 1.5 on both jets	2.1 μb
Require two B jets with p_T > 10 GeV/c	
Both B's in 30° < θ < 150°	2.7 μb
All B secondaries in 30° < θ < 150°	1.3 μb
Charged Multiplicity from both B	11
Additional Charged Particles in 30° < θ < 150°	13

(a) Steven Errede – Private Communication

$$\sigma^2 = A^2 + (B/p)^2 \quad , \qquad (3)$$

where A, B are constants and p is the particle momentum. For A, we have taken the quadratic combination of 5 μm solid-state detector resolution and 7 μm beam size. For B, we have taken two choices – 20μm GeV/c corresponding to scattering from a 0.5% radiator at 2 cm radius and 10 μm GeV/c corresponding to a 1 cm radius. This 0.5% is the sum of the beam pipe and the closest silicon layer (with strips assumed to run parallel to the beam). Table V(b) shows the corresponding probabilities. For good separation of B secondaries from normal hadrons ≥ 3σ signals are probably necessary. Their probabilities are 53% and 62%, respectively, per track, for each of the two error choices. Also of some interest is the minimum ratio of impact parameter to error for all the tracks of a given B decay. If this minimum is greater than 3, then all of the charged tracks are recognized and the charge of the B meson is established. As seen in Table V(c), this probability at the 3σ level is only 20% for the larger

Table V(a): Impact Parameter Distributions

I.P. (μm)	Probability	I.P. (μm)	Probability
0 – 10	0.15	60 – 70	0.03
10 – 20	0.09	70 – 80	0.03
20 – 30	0.06	80 – 90	0.03
30 – 40	0.05	90 – 100	0.02
40 – 50	0.05	100 – 200	0.16
50 – 60	0.04	300 – 400	0.04

Table V(b): Impact Parameter/Errors

I.P./Error (2 cm)	Probability	I.P./Error (1 cm)	Probability
0 – 1	0.26	0 – 1	0.20
1 – 2	0.13	1 – 2	0.11
2 – 3	0.08	2 – 3	0.07
3 – 4	0.07	3 – 4	0.06
4 – 5	0.04	4 – 5	0.05
> 5	0.42	> 5	0.51

Table V(c): Minimum Impact Parameters/Errors

I.P./Error (2 cm)	Probability	I.P./Error (1 cm)	Probability
0 – 1	0.50	0 – 1	0.42
1 – 2	0.21	1 – 2	0.17
2 – 3	0.09	2 – 3	0.12
3 – 4	0.03	3 – 4	0.06
4 – 5	0.02	4 – 5	0.04
> 5	0.15	> 5	0.19

error and 29% for the smaller error. The fractions of B decays for which all charged products have significant (3σ) impact parameters are thus relatively small.

Finally, we add that for leptons of momentum greater than 3 GeV/c (required for efficient detectors), the distribution of impact parameter over error closely follows the first set of entries in Table V(b), almost independently of the choice of vertex detector radius (because of the relatively high momentum).

We conclude with a reminder that several approximations have been made. First, charm decay lifetimes have been neglected in calculating impact parameters. This is not expected to produce any great changes in Table V. Second, in calculating the multiple scattering errors, we have neglected the fact that the tracks usually are not normal to the scatterers. This underestimates the scattering effects, and the advantages of the small pipe radius are greater than suggested by the numbers of Table V.

C. Application to CP Violation Study in B Decay

As indicated in Section IIB, the detection of CP violation through lepton charge asymmetries is expected to be very difficult because of the very small effects expected, unless new phenomena greatly enhance these effects. Therefore we have chosen to study CP violation through the detection of final states f into which both B and $\overline{B}$ can decay. The appropriate phenomenology is given in Section IIB.3. For the state f, we have chosen B_d, $\overline{B}_d \to \psi K_S$, a completely reconstructible state with a distinctive signature. Although the connection of K_S with a separate vertex may be difficult, the dilepton decay products of ψ can be so associated through a high resolution vertex detector, and can then be combined with the K_S decay products to obtain the known B_d invariant mass.

We then study the processes,

$$P + P \to B_a + B_b + X$$

$$B_a \to \psi K_S$$

$$B_b \to \ell^{\pm} + Y$$

where B_a, B_b are a $B\overline{B}$ pair of which at least one member is neutral, and $\ell^{\pm}$ is an electron or muon. CP violation manifests itself through a non-zero value of the asymmetry parameters A_f already defined in Section IIB3.

$$A_f = \frac{(\psi K_s,\ell^-) - (\psi K_s,\ell^+)}{(\psi K_s+\ell^{\pm})}$$

whose value, on the basis of the standard model, is expected to be in the range of a few percent.

We now apply the rate considerations above to the study of these processes. The main ingredients which go into a rate calculation are the following:

a) Cross section for two-B jets, $p_T > 10$ GeV/c, with all secondaries seen: 1.3 μb (Table IV). (Although for one of the decays only a lepton is required, it seems desirable to detect some of the other tracks to establish a B decay. There is at most a 1.4 factor to be gained by requiring only detection of the leptons).

b) We assume a $\psi K°$ branching ratio of 0.001. This is compatible with the ~1% upper limit to inclusive from B decay set by the CLEO experiment.

c) The ψ is detected through its e^+e^- or $\mu^+\mu^-$ decay modes with total branching ratio 14%. The $K^\circ \to K_S \to \pi^+\pi^-$ sequence has probability of 33%.

d) We require both leptons from the ψ to have 3σ impact parameter signals. Assuming the 1 cm pipe radius, we get from Table V(c) 29% probability. Since only two tracks are involved, this is probably an underestimate. By just squaring the single track 3σ probability from Table V(b), we get 0.63 x 0.63 = 40% which we use.

e) We require that the leptons from the second B decay have a 3σ impact parameter, with 53% probability. (Table V(b) + comment at the end of Section IVB.)

f) The lepton branching ratio from B decay is 24%. The probability that the lepton momentum be greater than 3 GeV/c is about 42%.

Thus, the effective cross section is:

$$\sigma_{eff} = 1.3\mu b \times 0.001 \times 0.14 \times 0.33 \times 0.40 \times 0.53 \times 0.24 \times 0.42$$

$$\sigma_{eff} = 1.3 \times 10^{-36} cm^2$$

For $L = 10^{32}$ cm^{-2} sec^{-1}, which appears at this time to be the optimistic maximum for vertex chamber experiments, we get $L = 10^{39}$ cm^{-2} year^{-1}, and ~ 1300 events per year. Even this is optimistic, since no instrumental or tracking efficiencies (other than geometrical ones) have been included.

We have to conclude that, at least for detectors in the central region, the situation is not very favorable.

It is of some interest to make comparisons with LEP and SLC. As we saw in Table III, the expected $B\overline{B}$ rate is 4 x 10^5 per 10^7 second year. Items (b), (c), and (f) above are applicable here too except for the 42% factor for lepton momentum since at the $Z°$ the B mesons have typically 30 GeV energy. Since $B\overline{B}$ production is 14% of the total cross section, items (d) and (e) are almost surely unnecessary. Indeed, no vertex chamber is really needed for this experiment. Thus the yearly rate is:

$$4 \times 10^5 \times 0.001 \times 0.14 \times 0.33 \times 0.24 = 4 \text{ events/year.}$$

Since there will be at least three LEP and one SLC detector capable of doing this experiment (as opposed to probably only one SSC detector), the total rate is of order 16 events/year.

We have not discussed the difficult trigger problem at SSC which is nonexistent at LEP or SLC. We conclude that the SSC advantage is not, at this stage, very compelling, and the experiment in question is probably impossible at LEP and very difficult at SSC.

D. Comments on Detection of Rare B Decay Modes

We consider here only those decay modes such as $B \to \mu e$, $K_S\mu e$ etc. for which all secondaries can be detected and complete reconstruction is possible. It is not clear that modes with missing neutrals can ever provide a sufficiently clean signature in a hadronic environment unless it turns out to be possible to make relatively clean B beams of useful intensity. We consider again detection in the central region already defined.

To be conservative we require that the secondaries of both B mesons be within the $30° < \theta < 150°$ angular interval corresponding according to Table IV to a 1.3 μb cross section. The additional factors determining the rate are the following:

a) All secondaries from the B decay under study to have $\geq 3\sigma$ impact parameter signals. We take this probability to be 0.40.

b) We require at least two secondaries from the second B decay to have $\geq 3\sigma$ impact parameter signals and assume a probability of unity for a typical hadronic decay with five charged secondaries.

Thus the typical cross-section is 1.3 x 0.4 = 0.5 μb, leading to 5 x 10^8 detected decays for an integrated luminosity of 10^{39} cm^{-2}. A branching ratio limit of $\sim 10^{-7}$ appears manageable if there are no other branching ratios (such as $K_S \to \pi^+\pi^-$ in $K_S\mu e$) involved. If we have been unduly conservative and only one B decay need be detected, the potential rate is increased by about a factor of five, and a limit close to 10^{-8} may be possible. In this case, the gross LEP/SCC rate of 4 x 10^5 times four detectors, may permit a branching ratio limit of order 10^{-5}. Again the SSC wins by about two orders of magnitude, provided background and trigger problems can be solved.

E. $B\bar{B}$ Detection in the Forward Region

J. Cronin has studied the detection of B meson pairs in the rapidity region $3 < y < 5$ with high resolution silicon detectors arranged in planes placed at distances 1 to 3 meters downstream from the interaction point. Details are discussed in Cronin's paper, but we quote the result that one might expect to identify $\geq 10^5$ double lepton events per year for studies of mixing and CP violation, and have 10^8–10^9 B mesons to search for rare two-body decay modes. These numbers are not terribly different from those expected for the central region detector discussed earlier, although the details of the detector design are of course quite different.

IV. Comments and Conclusions

We have examined the possibility of studying CP violation and rare decay modes of B mesons with the SSC. Although we have not considered in detail fixed-target experiments, it appears unlikely that the advantages of such experiments will outweigh the estimated factor of 100 reduction in rate (without obvious reduction of background) inherent in the lower center-of-mass energy. We can summarize our considerations in the following terms, assuming that we can operate tracking detectors and vertex devices at a luminosity of 10^{32} cm^{-2} sec^{-1}:

1) The SSC produces $B\bar{B}$ at a rate per year estimated to be three orders of magnitude larger than other hadron sources, and five orders of magnitude larger than LEP or SLC.

2) High resolution vertex detectors are essential for doing $B\bar{B}$ physics, and are almost surely required at some level of the trigger. While this is true for any other hadron source, it is not true for LEP/SLC in which 14% of all events at the Z° are $B\bar{B}$ pairs.

3) Rare B decay modes such as $\mu^+\mu^-$ or μ^+e^- which are completely reconstructable may be detectable at a branching ratio level of $\sim 10^{-7}$. Decay modes into non-reconstructable final states such as $\tau^+\nu$ or $\tau^+\tau^-$ look very difficult.

4) The study of CP violation via mixing in B° looks very difficult unless the effects are much larger than predicted by the standard model. Unlike K decay, both B and $\bar{B}$ decays from the same process must be detected. Lepton charge asymmetries are predicted to be very small ($\leq 10^{-3}$), and the asymmetric PP initial state will add systematic uncertainties to the statistical errors. CP violation in non-leptonic final states leads to larger expected asymmetries (a few percent) but the calculated event rates are at the level of 10^3 per year, probably too small to do definitive experiments.

5) The search for $B^{\circ}\bar{B}^{\circ}$ mixing effects (not including CP violation) is easier in that the mixing parameter r_2 (see Section II) is expected to be a few percent, and the dilepton rates are expected to be 10^5 per year. However the systematics of the asymmetric initial state may still be a serious problem; and, unless the mixing is very small, LEP/SLC may be a better bet to observe this mixing.

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8. The reader should be warned that Hagelin in Ref. 4 uses the notation $\Gamma = (\Gamma_1 + \Gamma_2)/2$, whereas Bigi and Sanda in Ref. 5 define $\Gamma = \Gamma_1 + \Gamma_2$ as in this paper. However in Ref. 6, Bigi and Sanda use an undefined Γ and inconsistently carry over some formulas from Ref. 4 and others from Ref. 5.

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