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REPORT OF THE B-FACTORY GROUP: I. PHYSICS AND TECHNIQUES*

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1. INTRODUCTION

The study of B meson decay appears to offer a unique opportunity to measure basic parameters of the Standard Model, probe for interactions mediated by higher mass particles, and investigate the origin of CP violation. These opportunities have been enhanced by the results of two measurements. The first is the measurement of a long B meson lifetime.[1)] In addition to allowing a simpler identification of B mesons and a measurement of the time of their decay, this observation implies that normal decays are suppressed, making rare decays more prevalent. The second measurement is that neutral B mesons are strongly mixed.[2)] This enhances the possibilities for studying CP violation in the B system.

The CESR storage ring is likely to dominate the study of B physics in e^+e^- annihilations for about the next five years. First, CESR has already reached a luminosity of 10^{32} cm^{-1} sec^{-1} and has plans for improvements which may increase the luminosity by a factor of about five. Second, a second-generation detector, CLEO II, will start running in 1989. It has been designed especially to study B meson physics in the 10 GeV region.[3)]

Given this background, the main focus of this working group was to ask what is needed for the mid- to late-1990 s. Many laboratories are thinking about new facilities involving a variety of techniques. To help clarify the choices, we focused on one example of CP violation and estimated the luminosity required to measure it using different techniques. This will be the subject of the next chapter. In Chap. 3 we will briefly describe the requirements for detectors matched to these techniques. In particular, we will give a conceptual design of a possible detector for asymmetric collisions (*i.e.*, beams of unequal energy) at the $\Upsilon(4S)$ resonance, one of the attractive techniques which will emerge from this study. A discussion of accelerator technology issues for using these techniques forms the second half of the B-factory Group report, and it follows in these proceedings.[4)]

2. TECHNIQUES FOR STUDYING CP VIOLATION

2.1 Introduction

Any high luminosity B-factory will permit the study of a large variety of issues in B physics including the properties of exclusive B decays, the measurement of $B\bar{B}$ mixing, the determination of Kobayashi-Maskawa (K-M) matrix elements, and the search for rare B decays. However, in

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Table 1. Estimation of the number of $B\bar{B}$ events required for CP violation studies at the SSC*

Class	Modes	Branching Ratio	Asymmetry	# $B\bar{B}$ Events Required
I. Charge Asymmetry in	$B_d \bar{B}_d \to l^{\pm} l^{\pm} + X$	0.01	10^{-3}	6×10^9
Same Sign Dileptons	$B_s \bar{B}_s \to l^{\pm} l^{\pm} + X$	0.02	10^{-4}	2×10^{12}
II. Mixing with Decay	$B \to \psi K_s$	5×10^{-4}	0.05–0.3	(1-34) $\times 10^8$
to a CP Eigenstate	$B \to \psi K_s X$	2×10^{-3}	0.05–0.3	(2-85) $\times 10^7$
	$B \to D\bar{D}K_s$	5×10^{-3}	0.05–0.3	(3-100) $\times 10^7$
	$B \to \pi^+\pi^-$	5×10^{-5}	0.05–0.5	(0.3-32) $\times 10^8$
	$B \to D^{*+} D^-, D^+D^-, D^* D^*$	3×10^{-3}	0.05–0.3	(0.7-26) $\times 10^8$
III. Mixing with Decay	$B_d \to D^+\pi^-$	6×10^{-3}	0.001	3×10^{11}
to a CP Non-Eigenstate	$B_d \to D^0K_s$	6×10^{-5}	0.01	7×10^{11}
	$B_s \to D_s^+K^-$	3×10^{-4}	0.5?	5×10^7
IV. Cascade Decays to the	$B^- \to D^0 K^- + X$	10^{-5}	0.1?	9×10^8
Same Final State	$\hookrightarrow K_s + Y$			
V. Interference of Spectator	$B^- \to D^{*0} \bar{D}$	3×10^{-3}	0.01	2×10^9
and Annihilation Graphs				
VI. Interference of Spectator	$B^- \to K^-\rho^0$	$\sim 10^{-5}$	0.1	1×10^8
and Penguin Graphs	$\bar{B}_d \to K^-\pi^+$	$\sim 10^{-5}$	0.1	1×10^8

*The specific channels considered here for each class of asymmetry are illustrative and not exhaustive. At this time we need to keep an open mind as to which channels will be best suited for CP violation studies. In this spirit we have included among the modes illustrating Class II asymmetries $\psi K_s X$ and $D\bar{D}K_s$, which are not necessarily CP eigenstates. There is some danger of a cancellation between the asymmetries produced by sub-channels with opposite CP quantum numbers, but a total cancellation is unlikely.

this study, we focus on CP violation because it is the one important issue which may not be adequately addressed by present or near future accelerators.

CP violation in the B system can manifest itself in a number of different ways. Table 1, taken from the 1987 Berkeley SSC Workshop,[5] shows six classes of CP violation along with branching ratios, estimated asymmetries, and the estimated number of $B\bar{B}$ events needed to observe the effect *at the SSC*. We chose to study a decay mode from Class II, "Mixing with Decay to a CP Eigenstate," because this class offers the following particular advantage. In the standard model, the CP-violating asymmetries for such decays depend only on values for elements of the K–M matrix, which, in principle, can be determined from measurements that do not involve CP violation.[6] For this case, the decay of a B or $\bar{B}$ can proceed either directly or following mixing. The CP-violating amplitude arises from interference between the two spectator-diagram processes; all of the hadronic physics drops out of the asymmetry because only a single amplitude is involved.[7]

Thus, from our present measurements of the K–M matrix, we can set limits on the magnitude of this form of CP violation if it is generated from the K–M phase within the three-generation standard model.[8] In the same way, once measured, the result can be easily interpreted. If the result falls outside the bounds given by the three-generation standard model, CP violation must, in part, come from a different source. This is not the only form of CP violation that we wish to investigate, but it is sufficiently basic that any new effort aimed at CP violation in B decays should include the capability of studying it.

We used the decay mode $B^0 \to \psi K_s$ in large part because there was a careful study of this mode submitted to the workshop by Aleksan et al., for the case of an asymmetric $\Upsilon(4S)$ collider.[9] Other Class II decays would probably yield similar results.

From present limits on K–M parameters, the predicted limits on the CP–violation asymmetry parameter, $\sin\phi(\psi\ K_s)$, are

$$0.1 \leq \sin\phi(\psi K_s) \leq 0.6 \ , \tag{1}$$

where the upper part of the range is preferred for relatively low top-quark masses (60 to 80 GeV/c^2).[5] (The parameter $\sin\phi$ is twice the time-averaged asymmetry listed in Table 1.)

2.2 General Technique

In the presence of CP violation, the B and $\bar{\mathrm{B}}$ rates to a CP eigenstate, ψK_s in our case, will evolve differently with time:[7]

$$R(B^0 \rightarrow \psi K_s) \propto e^{-\Gamma t}\,[1 + \sin\phi \sin(x\Gamma t)]$$

$$R(\bar{B}^0 \rightarrow \psi K_s) \propto e^{-\Gamma t}\,[1 - \sin\phi \sin(x\Gamma t)] \ , \tag{2}$$

where R is the rate of the decay process, $x = \Delta m/\Gamma$, and Δm is the mass difference between the two neutral B meson mass eigenstates. Note that the B and $\bar{\mathrm{B}}$ in Eq. (2) refer to the identities of the particles at the time they are created, rather than at the time they decay.

Since the b and $\bar{\mathrm{b}}$ quarks are produced in pairs, the general technique is to observe a neutral B decaying to ψK_s and determine whether it was originally a B^0 or a $\bar{B}^0$ by tagging it, *i.e.*, by detecting the decay of the other B in a flavor-specific mode. In the following sections, we will explore how this general technique is modified by special situations involving the symmetries of the initial state and special tagging techniques. In particular, we will indicate how the intrinsic asymmetry $\sin\phi$ is diluted to $d \cdot \sin\phi$ ($d < 1$) for each technique.

2.3 Case 0: Symmetric Collisions at the Υ(4S)

We start with the case which applies to present symmetric (*i.e.*, beams of equal energy) storage rings, such as CESR, running on the Υ(4S) resonance. This has been listed as Case 0 because we will see that the above technique does not work in this situation.

The advantages of studying B's at the Υ(4S) are well known:

1. The resonant cross section is about four times higher than the continuum cross section for $b\bar{b}$ production slightly above the resonance.
2. The final state is clean and well understood. It consists solely of $B^0\bar{B}^0$ and B^+B^- pairs.
3. Due to the simple final state, the well-determined beam energy can be used as a constraint leading to very good mass resolution and low backgrounds.

The Υ(4S) is a C = −1 resonance decaying exclusively into $B\bar{B}$. The symmetry of the wave function changes the general formula because the two B's develop as a coherent state. The time development for this case is:

$$R(B^0\bar{B}^0 \rightarrow B^0\psi K_s) \propto e^{-\Gamma(t'+t)}\{1 + \sin\phi \sin[x\Gamma(t'-t)]\}$$

$$R(B^0\bar{B}^0 \rightarrow \bar{B}^0\psi K_s) \propto e^{-\Gamma(t'+t)}\{1 - \sin\phi \sin[x\Gamma(t'-t)]\}, \tag{3}$$

where t and t' are the times at which the ψK_s and the flavor-specific decay occur, respectively.[7]

The time development is in the difference of the two decay times. This can be understood in a simple way: Both the B and $\bar{\mathrm{B}}$ begin mixing into the charge conjugate states after they are produced, but with a relative phase which remains constant, so that the two states are always orthogonal. Thus, when the first decay occurs, the wave function collapses with the second B the charge conjugate of the first. The second B then begins to mix into its charge conjugate state. This process is often described as "nothing happens until the first decay takes place."

Since the asymmetry is odd in $(t' - t)$, it integrates to zero if the time difference of the decays is not measured. At a symmetric Υ(4S) collider, the mean decay length of B's is about 30 μm, a distance which is insufficient for the measurement of $(t' - t)$.

We will see there is still a way to measure this class of CP violation at a symmetric 10 GeV collider in Case 2.

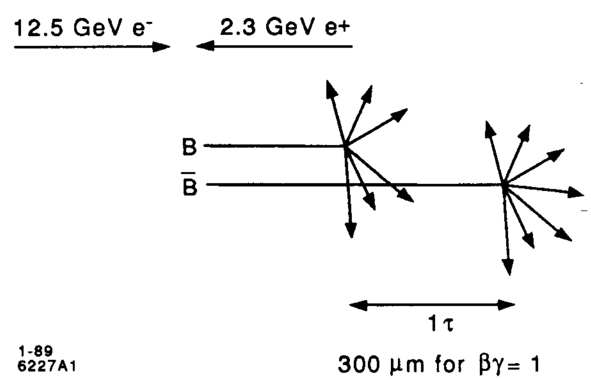

Fig. 1. Schematic of a $B\bar{B}$ decay in an asymmetric collider at the Υ(4S).

2.4 Case 1: Asymmetric Collisions at the Υ(4S)

Consider a collider running at the Υ(4S) resonance, but with unequal beam energies,[10] as illustrated in Fig. 1. The two B's from the Υ decay are almost at rest in the center-of-mass, but are moving in the laboratory. For the example shown in Fig. 1, a 12.5 GeV electron beam against a 2.3 GeV positron beam, the center-of-mass moves with $\beta\gamma = 1$. The two B decays will be separated, on average, by one lifetime, or 300 μm in this example.[11]

Assuming one can measure $\Delta t \equiv (t' - t)$, but not $(t' + t)$,[12] Eqs. (3) imply

$$R(\Delta t) \propto e^{-\Gamma|\Delta t|}[1 \pm \sin\phi \sin(x\Gamma\Delta t)] \ . \tag{4}$$

By fitting to the time dependence of Eq. (4), one should be able to obtain an asymmetry of $0.61 \sin\phi$ (*i.e.*, a dilution factor $d = 0.61$).[13] This calculation allows for the uncertainties in Δt, due both to the fact that the distance between the B decay points is smeared slightly by the center-of-mass motion of the B's and to experimental resolution. It does not include the effect of incorrect tags, which we will account for separately in Sec. 2.9.

This method thus combines all the advantages of the symmetric $\Upsilon(4S)$ case with the ability to measure the time development of the final state. This technique also yields an advantage in suppressing combinatoric backgrounds since the origin of most charged particles can be determined. However, both the detector and the collider are somewhat more difficult to build. We will return to the former in Chap. 3 and the latter in our report on accelerator technology.[4]

2.5 Case 2: Symmetric Collisions Just Above the Υ(4S)

One can measure Class II CP violation with a symmetric 10 GeV collider by running just above the $\Upsilon(4S)$ resonance.[7,14] Above $B\bar{B}^*$ threshold, but below $B^*\bar{B}^*$ threshold, $B\bar{B}^*$ production should be the dominant $b\bar{b}$ final state. This yields a $C = +1$ $B\bar{B}$ state since the B^* decays into $B\gamma$.

For this case, the time development changes from Cases 0 and 1, in that $(t' - t)$ becomes $(t' + t)$:

$$R(B^0\bar{B}^0 \to B^0\psi K_s) \propto e^{-\Gamma(t'+t)}\{1 - \sin\phi \sin[x\Gamma(t' + t)]\}$$

$$R(B^0\bar{B}^0 \to \bar{B}^0\psi K_s) \propto e^{-\Gamma(t'+t)}\{1 + \sin\phi \sin[x\Gamma(t' + t)]\} \ . \tag{5}$$

As before, both the B and $\bar{B}$ begin mixing into the charge conjugate states after they are produced, but with the opposite rather than the same phase. Thus, when the first decay occurs, the second B is already mixed and continues to mix until it decays.

Since $(t' + t)$ is even, integration of the asymmetry over both times leads to a finite value. The dilution factor resulting from this integration[15] is

$$d = \frac{2x}{(1 + x^2)^2} \ . \tag{6}$$

This value assumes that any $C = -1$ contributions, *i.e.*, $e^+e^- \to B\bar{B}$ reactions, are separable. CP violation can be measured, but at a cost of not having the resonant enhancement of the $\Upsilon(4S)$.

2.6 Case 3: Symmetric Collisions in the Continuum

A (presumably) symmetric collider in the continuum, say 8 GeV per beam, would allow the time development of the B decays to be measured. However, one gives up all the advantages of the $\Upsilon(4S)$ resonance and suffers a cross section reduction as E^{-2}. The B decays develop incoherently in this region, so the general formulae, Eqs. (2), apply directly. Their application requires knowledge of the primary interaction point (unlike Cases 1 and 2).

However, the asymmetry is diluted by mixing of the tagging particle. If f_0, f_-, f_s, and f_Λ are the fractions of b quarks which hadronize as $\bar{B}^0$, B^-, $\bar{B}_s$, and B-baryons, respectively, then

$$R(t) \propto e^{-\Gamma t}\left[1 \pm \left(f_- + f_\Lambda + \frac{f_0}{1 + x^2}\right) \sin\phi \sin(x\Gamma t)\right] \ , \tag{7}$$

where we have assumed that B_s's are fully mixed. Assuming that fitting this time spectrum leads to similar dilution as for Case 1, then the overall dilution factor is

$$d = 0.61\left(f_- + f_\Lambda + \frac{f_0}{1 + x^2}\right) \simeq 0.61\left(0.50 + \frac{0.35}{1 + x^2}\right) \tag{8}$$

for a reasonable model.

2.7 Case 4: Z Decay without Polarization

If we consider a collider at the Z mass without longitudinal polarization, then this case is the same as the previous case except that there is a considerable resonant enhancement from the Z:

$$\frac{\sigma(e^+e^- \to b\bar{b})_{\sqrt{s}=m_Z}}{\sigma(e^+e^- \to b\bar{b})_{\sqrt{s}=16\ \mathrm{GeV}}} \approx 60 \ . \tag{9}$$

2.8 Case 5: Z Decay with Polarization

The situation at the Z mass becomes even more attractive if longitudinal electron polarization is available.[16] This is relatively easy at a linear collider[17] and is under consideration for LEP.[18]

With a polarized electron beam on the Z resonance, there is a large forward-backward asymmetry in the b versus $\bar{b}$ direction (A^b_{FB}):

$$A^b_{FB} \approx \frac{3}{4}\mathcal{P}\frac{2v_b a_b}{v_b^2 + a_b^2} \approx \frac{3}{4}\mathcal{P}(0.94) \quad , \tag{10}$$

where $\mathcal{P}$ is the magnitude of the polarization. The asymmetry is almost maximal and would be an extremely effective B tagging mechanism for complete polarization.

Table 2. Comparison of B–Factory Techniques

Factor/Case	Asymmetric $\Upsilon(4S)$	Symmetric $\Upsilon(4S)+$	$\sqrt{s} = 16$ GeV	Z $\mathcal{P} = 0$	Z $\mathcal{P} = 0.9$ ($\mathcal{P} = 0.45$)
$b\bar{b}$ cross section, σ (nb)	1.2	0.3	0.11	6.3	6.3
Fraction of B^0, f_0	0.43	0.34	0.35	0.35	0.35
ψK_s reconstruction efficiency, ϵ_r	0.61	0.61	0.61	0.46	0.46
Tag efficiency, ϵ_t (and method)	0.48 (ℓ, K)	0.48 (ℓ, K)	0.30 (ℓ, D)	0.18 (ℓ, D)	0.61 (A_{FB})
Wrong tag fraction, w	0.08	0.08	0.08	0.08	0.125 (0.27)
Asymmetry dilution, d	0.61	0.63	0.45	0.45	0.61
$\int \mathcal{L}dt$ needed for 3σ effect (10^{40} cm^{-2}) *	0.45–16	2.1–77	18–640	0.68–25	0.14–5.0 (0.37–13)
Relative $\int \mathcal{L}dt$ needed	1.0	4.7	40	1.5	0.3 (0.8)

*peak luminosity needed in units of 10^{33} cm^{-2} sec^{-1} for 10^7 seconds of fully efficient running at peak luminosity.

Also note that the additional dilution due to mixing, included for Cases 3 and 4, does not apply here. Present techniques for producing longitudinally polarized beams in linear accelerators limit the polarization to 50% due to a spin degeneracy. There are active programs to find ways of producing polarizations approaching 100%.[19]

2.9 Evaluation of the Different Techniques

The needed integrated luminosity to measure CP violation to a given degree of accuracy can now be calculated for each of the above techniques by using the following formula:

$$\int \mathcal{L}dt = \left\{\sigma(e^+e^- \to b\bar{b}) f_0 2B\epsilon_r\epsilon_t\left[(1-2w)d\delta(\sin\phi)\right]^2\right\}^{-1}, \tag{11}$$

where:

- f_0 is the fraction of B^0's in the b quark fragmentation (for Case 2, only $C = +1$ $B\bar{B}$ states are counted);
- B is the product of branching fractions to the desired mode (assumed to be 5×10^{-4} for the ψ K_s mode times 0.14 for the leptonic decay modes of the ψ);
- ϵ_r is the ψ K_s reconstruction efficiency;
- ϵ_t is the tagging efficiency, *i.e.*, the fraction of events in which the flavor of the B decaying to a flavor-specific state can be measured;
- w is the fraction of incorrect tags;
- d is a dilution factor which takes into account the loss in asymmetry due to fitting, integrating over time, and/or the mixing of the tagged decay (taking $x = 0.7$); and
- $\delta(\sin\phi)$ is the required accuracy on the CP asymmetry parameter $\sin\phi$, taken to be 1/3 of $\sin\phi$ in this case in order to give a 3σ effect.

Table 2 gives the factors that we put into Eq. (11) for each of the five cases and the resulting requirement on integrated luminosity. The numbers for the first case, an asymmetric $\Upsilon(4S)$ collider, were taken from Aleksan et al.,[9] and the other cases were scaled from this work by making reasonable assumptions. Aleksan et al., assume a very good detector (see Chap. 3) in their simulation. Thus, the required luminosities will be larger for less-than-optimum detectors.

The ψK_s reconstruction efficiency, ϵ_r, is assumed to be smaller on the Z than at lower energies because it was assumed that the neutral decays of the K_s could not be reconstructed at the Z mass. In a similar way, the tagging efficiency, ϵ_t, decreases with increasing energy because the techniques change and become less efficient. At the $\Upsilon(4S)$, Aleksan et al.,[9] showed that kaons could be used for tagging if events which had extra kaons were discarded. It was assumed that this would not work in the continuum because too many extra kaons would be produced. However, tagging with reconstructed D's would be possible there. At the higher energy of the Z mass, it was assumed that both the D and lepton reconstruction efficiency would drop. For Case 5, Z decay with polarization, $(1-2w)$ is replaced with A^b_{FB} from Eq. (10) and the tagging efficiency is taken from Ref. 16.

The penultimate row of Table 2 gives the range of integrated luminosities needed to measure CP violation to three standard deviations. There is a factor of 36 in each of these ranges since there is a factor of six in the allowable range of $\sin\phi$ from our present knowledge of the K–M matrix [see Eq. (1)]. The final row of the table gives the relative amount of integrated luminosity needed for each technique normalized to unity for the asymmetric $\Upsilon(4S)$ collider. The asymmetric $\Upsilon(4S)$ collider and Z factories, with or without longitudinal polarization, require the least integrated luminosity. In the second part of this working group's report,[4] we will explore the prospects for obtaining colliders with luminosities in the required range.

3. EXPERIMENTS FOR STUDYING CP VIOLATION

3.1 Introduction

In this chapter we consider the particular features of experiments which will be important for the measurement of CP violation. We will continue to use the $B \to \psi K_s$ mode as an example. Our main concern is to identify the important issues that affect collider and detector design. We will begin with some general comments about detectors that are generic to the different techniques outlined in the previous chapter. After a short summary of some considerations that influence collider design, we will discuss issues that are specific to each case. The principal detector resources required for a measurement of CP violation in $B \to \psi K_s$ are:

- Vertex Detection.

  All techniques except Case 2 require excellent vertex resolution in order to measure the difference between the decay times of the two B mesons.

- $B \to \psi K_s$ Reconstruction.

  The product of the branching ratios for $B \to \psi K_s$ and the leptonic modes of the ψ is small ($\approx 7 \times 10^{-5}$). B mesons that decay this way must be reconstructed with little background.

- $B - \bar{B}$ Tagging.

  The measurement of the CP violation asymmetry depends on efficiently and accurately determining if the other B meson decayed as a B or a $\bar{B}$. This requires excellent lepton and charged kaon identification.

Detectors that can efficiently exploit these techniques can be designed with some confidence, based on the accumulated experience of designing and operating detectors at e^+e^- colliders. The most revolutionary detector appears to be the one required for the asymmetric collider option, because it must cover the forward region with sufficient precision. We discuss some of our thoughts on this subject and present a conceptual design of a detector. For the other cases, we only include an outline of the features required for observing CP violation in $B \to \psi K_s$

3.2 Vertex Detection

Silicon vertex detectors appear to be the only viable solution to the problem of reconstructing decay vertices with sufficient accuracy to measure the difference in decay times between the two B mesons. Silicon detectors can have the required resolution (in the 10 μm range in two dimensions) with sufficient segmentation (approximately 10,000 channels per layer) so that track overlap is not a problem. The alternative technology, drift chambers, lacks the inherent resolution for this problem, particularly in the measurement of the position of the track along the beam. Due to the constraints of space around a 1 cm beam pipe, it appears to be impossible to build a wire chamber with sufficient segmentation along the beam to avoid inefficiencies due to track overlap.

A number of fixed target experiments have successfully used silicon detectors, and SLC and LEP will soon provide experience in using them at e^+e^- colliders.[20] General features of a silicon vertex detector for a B factory operating at the $\Upsilon(4S)$ have been studied,[21] and precision vertex detection has been included in the design of a proposed detector.[22]

The particles resulting from the decay of the $\Upsilon(4S)$ have quite low momenta, even with the boost of an asymmetric collider. Multiple Coulomb scattering in the beam pipe and the first (few) layer(s) of the vertex detector can dominate the vertex resolution, even at high energy colliders. This places severe constraints on the beam pipe radius which, in turn, becomes a significant problem of the collider design, as discussed in the accelerator part of our report.[4] The small beam pipe can also become a detector problem by introducing high backgrounds in the detector due to scattered particles.[23]

3.3 $B \to \psi K_s$ Reconstruction

The $B \to \psi K_s$ mode studied here has a particularly simple event topology. In particular, the tracks from these decays will be well separated from the tracks from the other B meson, if vertex resolution is adequate to separate the vertices of the two B mesons. To avoid mixing these events with $\psi K_s \pi^0$ events, which have the opposite value of CP, the energy and mass resolution of the detector must be adequate to discriminate against slow π^0's.

The interaction between momentum resolution in the detector and the energy spreads of the e^+e^- collider beams in determining the resolution in total energy and reconstructed B meson mass is discussed in a contribution to these proceedings.[24] For experiments at the $\Upsilon(4S)$, the resonance width acts as a monochrometer, sharply limiting the influence of the collider beam energy spread on the total energy or mass resolution of a reconstructed B meson. (Of course, a small collider beam energy spread is still important in concentrating the luminosity in the useful energy region.) Thus, the reconstruction resolution requirements have little influence on collider design, but greatly influence detector design.

Some combination of dE/dx, time of flight, electromagnetic shower counters and iron absorbers are standard equipment for particle identification in e^+e^- collider experiments. The authors of the PSI proposal have recognized[22] that this may not be adequate for reconstructing low multiplicity B decays with high-momentum hadrons, even for experiments at the $\Upsilon(4S)$. Their response has been to include ring-imaging Čerenkov (RICH) counters in their design.

Although we focussed on $B \to \psi K_s$ for this study, it is essential that a detector to search for CP violation be capable of reconstructing more complicated decay modes in order to maximize the opportunity of discovering CP violation and developing an understanding of it after it has been found. Reconstruction of these more complicated modes will generally require better momentum resolution and particle identification than that required for $B \to \psi K_s$.

3.4 B–$\bar{\text{B}}$ Tagging

Tagging the other B meson as having decayed as either a B or a $\bar{\text{B}}$ is accomplished by identifying the sign of a lepton or charged kaon. Without clear secondary vertex separation, only high momentum leptons (above about 1.4 GeV in the $\Upsilon(4S)$ frame) are useful for the lepton tag, since low momentum leptons can come from semileptonic decays of D's from $B \to DX$ decays. Measurements of $B\bar{B}$ mixing by UA1,[25] ARGUS,[26] and CLEO[27] demonstrate that this tagging is possible at both low and high energy colliders. Aleksan et al.,[9] showed that muons with momenta between 0.8 and 1.4 GeV could also be used if they could be established as coming from the primary vertex.

B–$\bar{\text{B}}$ tagging via charged kaons is limited by Cabibbo-suppressed D decays and the reliability of K/π separation. The Cabibbo-suppressed D decays background can be minimized by rejecting events with excess kaons.[9] The reliability of the K/π separation is an essential detector design consideration; in addition to the usual dE/dx in a central drift chamber, a time of flight and/or a RICH system may also be required.

The B–$\bar{\text{B}}$ tagging requirement has little direct influence on collider design but it has a major impact on detector design, except for Case 5.

3.5 Influences on Collider Design

The requirements for an experiment to observe CP violation have the following general influences on collider design:

- High Luminosity.

  The high luminosities required appear to be the major challenge for collider design.
- Low Background Rates.

  High luminosities imply large beam currents which intrinsically lead to high background rates in the detector. To avoid background, the vacuum near an interaction region must be excellent and the region and nearby lattice must be carefully designed to avoid illuminating the beam pipe with direct or scattered synchrotron radiation or stray particles from the beams.
- Beam Pipe Radius.

  The beam pipe radius must be small for all techniques except Case 2, and even in this case a small beam pipe is useful in separating secondary D decays from the primary B decays. This requirement substantially increases the difficulty of achieving low background rates.
- Beam Pipe Thickness.

  If decay times must be measured, the beam pipe must be thin in order to reduce multiple scattering, On the other hand, it must be thick enough to shield sensitive vertex detectors from RF radiation from the beam and be coated to absorb soft synchrotron radiation.
- Beam Energy Spread.

  A small beam energy spread is important for colliders operating at or near the $\Upsilon(4S)$ in order to take advantage of the resonance width. In the other cases this spread is much less important.

3.6 Case 1: Asymmetric Collisions at the $\Upsilon(4S)$

The two novel issues for a detector at an asymmetric $\Upsilon(4S)$ collider are (1) the problems caused by folding the solid angle forward and (2) the need to detect separate B decay vertices along the beam direction. To understand these issues, we sketched such a detector at the Summer Study; it is shown in Fig. 2. We took the beam energies to be 12.5 GeV versus 2.3 GeV for this study ($\beta\gamma = 1$) and used the interaction region design specified by Garren.[28]

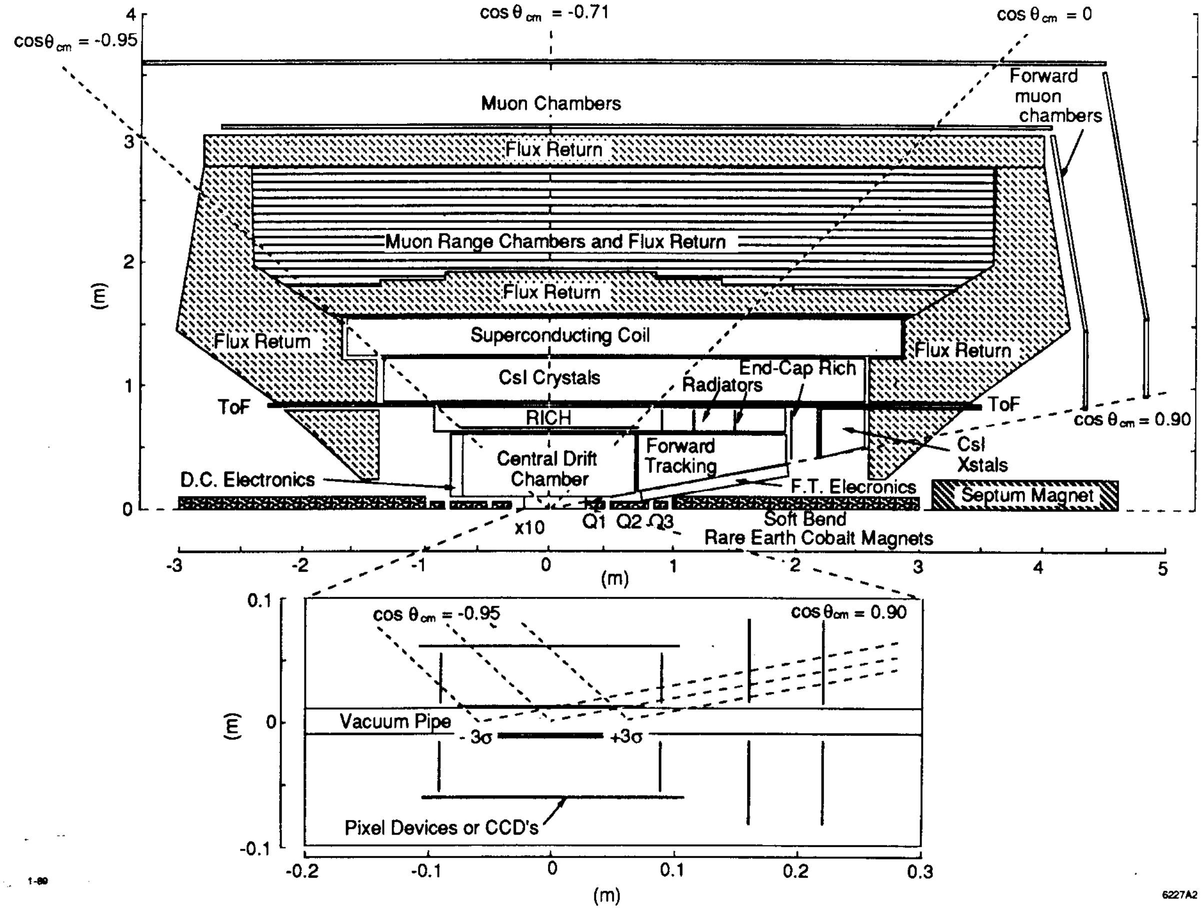

Fig. 2. A detector for an asymmetric collider at the $\Upsilon(4S)$.

For less asymmetric detectors, the solid angle issues are less severe, but the B's separate a smaller amount.[11]

Our goal was to design a detector which would approximate the near ideal detector assumed in the Aleksan et al., study.[9] In designing it, we borrowed freely from ideas which have been used in the building the CLEO II detector[3] and in the detector designed for the PSI proposal.[22]

Solid Angle Considerations. To obtain high efficiency for reconstruction and tagging, it is essential to cover greater than 90% of the center-of-mass solid angle. The detector in Fig. 2 has full vertex detection, tracking, particle identification, and calorimetry over 92.5% of the solid angle, $-0.95 < \cos\theta_{c.m.} < 0.90$. In the laboratory, this requires coverage from 11° to 132°. The forward angle is limited by the rare earth cobalt quadrupole magnets, which start 30 cm from the interaction point in the Garren design.[28]

These considerations lead to the need for a forward detector. Both it and the barrel detector individually are quite conventional; indeed, the barrel design is essentially a modest extrapolation of the PSI proposal. However, the interface between the barrel and the forward detectors will require some ingenuity in order to reduce multiple scattering to an acceptable level.

Vertex Detection. There are several issues concerning the vertex detection. First, in order to achieve sufficient resolution in the vertex position, the beam pipe radius must be small (between about 1 to 1.5 cm).[9] This radius is much smaller than any that has been used so far, so considerable effort will be required to design collider optics and masking that will yield acceptable background rates. A suitable synchrotron radiation masking scheme for the Garren design has not been studied yet.

Second, the bunch length is typically about 2 cm,[28] which is longer than the radius at which detectors are placed. This makes it difficult to design a detector in which the particles always cross the detector at close to normal incidence. The interaction region enlargement in Fig. 2 shows an attempt to have a reasonable placement of detectors. The dotted lines show solid angle envelope for particles emitted from the interaction point and from ±3 standard deviations in the beam direction.

Third, the requirement for three-dimensional vertex reconstruction argues for silicon devices with two-dimensional readouts, such as CCD[29] or silicon diode arrays.[30]

Charged Particle Tracking. In a 1.5 T field, the required (measurement dominated) momentum resolution[9] of

$$\frac{\sigma_p}{p} = 0.004p \quad (p \text{ in GeV/c}) \tag{12}$$

can be obtained by the combination of the vertex detector and a 50 layer drift chamber in the radial region from 10 to 60 cm, if each measurement has an error of 100 μm. The SLD Collaboration is building a large chamber with a measurement error in this range.[31]

Particle Identification. Since π/K separation is only needed to about 3 GeV/c at the $\Upsilon(4S)$, a thin RICH counter consisting of a 1 cm NaF crystal radiator and a 13 cm gap is adequate. See Ref. 22 for a detailed discussion.

Photon Detection. Good photon detection and reconstruction is essential for reconstructing B mesons. The best choice for the 10 GeV center-of-mass energy region appears to be CsI crystals.[3,22] Beam tests on crystals for the CLEO II detector give an energy resolution of 4% for 180 MeV photons.[32] Because of the small tracking volume used in this design, even with the forward detector, the total volume of CsI crystals is smaller here than in the CLEO II detector.

Muon Detection. Detection of muons with momenta as low as 800 MeV/c is useful for B–flavor tagging and ψ reconstruction. However, conventional muon detection with thick absorbers and chambers is difficult in this region due to hadron punch-through. The solution used in this design is to take advantage of the difference between pion and muon range by using a muon range detector to cover the 0.8 to 1.2 GeV/c momentum region.[33] Such a detector could be built with 0.5 to 1 cm iron plates separated by thin chambers. Above 1.2 GeV/c, the difference in range approaches the straggling error, and the method loses usefulness. More detailed calculations are needed to establish the utility of this technique.

3.7 Case 2: Symmetric Collisions Just Above the $\Upsilon(4S)$

The detector requirements for symmetric colliders just above the $\Upsilon(4S)$ are well-understood, because this is the energy range in which the CLEO and ARGUS experiments have been successful in reconstructing B mesons. A detector to search for CP violation would likely be constructed along the lines of the CLEO II detector or the PSI proposal. Very precise vertex detection is not crucial in this technique, since separation of B vertices is not required. However, good vertex detection would be a very useful tool for reducing backgrounds by separating D decay products from B decay products.

The mass resolution of the detector must be very good for this technique to succeed because it must be possible to separate reconstructed B mesons coming from $B^0\bar{B}^{*0} \to B^0\bar{B}^0\gamma$ events, where the γ is not detected, from those coming from the direct production of $B^0\bar{B}^0$. The latter could be a serious background. In the first case, if the energy of the B meson candidate is assumed to be half of the total energy, the reconstructed B mass will be about 26 MeV ($\approx E_\gamma/2$) above the true B mass. In the latter case, the B will reconstruct to the correct B mass. The separation of these two types of events depends on the mass resolution of the experiment which, in turn, depends on the energy spread of the collider beams, the momentum resolution of the detector, and the Doppler shift of the B's resulting from $\bar{B}^{*0}$ decay. The resolution of the CLEO detector would be quite adequate[24] to separate these two types of events. The experiment would be very difficult if the mass resolution were noticeably worse.[34]

An alternative would be to detect the photon from $\bar{B}^{*0} \to \bar{B}^0\gamma$, but it appears very difficult to accomplish this with high efficiency.

3.8 Case 3: Symmetric Collisions in the Continuum

At an e^+e^- collider operating near 16 GeV, B mesons are typically produced with $\beta\gamma$ near 1. This matches the asymmetric collider in our study, so in order to measure the decay times of the B mesons with sufficient accuracy, a beam pipe with a radius not much larger than 1 cm will again be required. The rest of the detector can be quite conventional; CLEO II or the PSI proposal can serve as a model. Compared to experiments operating at the $\Upsilon(4S)$, the total energy constraint is lost, and the mass resolution is much worse because the beam energy cannot be used. This implies that an experiment must rely much more heavily on vertex detection for eliminating combinatorial background in B reconstruction.

3.9 Case 4: Z Decay without Polarization

The large B meson rate at the Z has encouraged a large amount of thought about how to detect them efficiently. B mesons resulting from Z decay typically have $\beta\gamma$ in the neighborhood of five to seven. As far as reconstruction of B vertices is concerned, a larger, more conventional, beam pipe radius could be adequate. However, eliminating the large background from charm decays will require excellent vertex detection. Again, there is no total energy constraint to reduce combinatorial background and the mass resolution will be poor, so reconstruction of B decays must rely very heavily on vertex detection.

Compared to Cases 1 to 3, the higher momentum of the tracks implies that it is harder to achieve comparable momentum resolution, and the exclusion of π^0 background from the reconstructed B mesons will be more difficult. Furthermore, in this case tagging the decay of the other B is likely to be harder than at lower energy due to backgrounds.

On the other hand, this case has a number of attractive features: the event rate is high; the large data sample would have enormous potential for physics outside of B meson physics; and the primary vertex will usually be tagged by extra particles from the Z decay, so the decay time can be directly measured. Experience soon to be gained at SLC and LEP should show how easy or difficult it will be to overcome the experimental obstacles.

3.10 Case 5: Z Decay with Polarization

For this case the experiment and detector are basically the same as for Case 4, except that the effort that must be expended on lepton identification for tagging can be substantially reduced, since the tagging is primarily accomplished by the polarization. However, lepton identification is needed in any case to reduce background in reconstructing the ψ, and tagging with leptons will be a useful check on the polarization tag.

4. CONCLUSIONS

It appears that the measurement of CP violation in the B system with e^+e^- colliders is difficult, but not impossible. There are several attractive options, each with its own advantages and drawbacks. Asymmetric colliders at the $\Upsilon(4S)$ and colliders on the Z resonance, with or without polarization, require the least luminosity. Symmetric colliders running just above the $\Upsilon(4S)$ require slightly more. In any case, high luminosities (minimums of a few times 10^{33} to 10^{34} cm^{-1} sec^{-1}) are required to get well into the range in which CP violation can occur. The possibilities of obtaining these luminosities will be the subject of the following paper. The detectors required to measure CP violation are sophisticated, but within the limits of present technology.

FOOTNOTES AND REFERENCES

1. For a summary of recent results see S. L. Wu, *Proceedings of the 1987 International Symposium on Lepton and Photon Interactions at High Energies*, ed. by W. Bartel and R. Ruckl (North Holland, Amsterdam, 1988), p. 39.
2. H. Albrecht *et al.*, *Phys. Lett.* **192B**, 245 (1987); N. Katayama, *Proceedings of the SLAC Summer Institute on Particle Physics* (July 1988), ed. by E. C. Brennan (to be published).
3. CLEO Collaboration, Cornell report CLNS-85/634 (1985).
4. R. H. Siemann *et al.*, following paper in these proceedings.
5. K. J. Foley *et al.*, *Proceedings of the Workshop on Experiments, Detectors, and Experimental Areas for the Supercollider,* July 7-17, 1987, Berkeley, California, ed. by R. Donaldson and M. G. D. Gilchriese (World Scientific, Singapore, 1988), pp. 701-727.
6. R. D. Peccei *et al.*, these proceedings.
7. I. I. Bigi and A. I. Sanda, *Nucl. Phys. B* **193**, 85 (1981); *Nucl. Phys. B* **281**, 41 (1987); I. I. Bigi, V. A. Khoze, N. G. Uraltsev and A. I. Sanda in *CP Violations* (World Scientific Series on Directions in High Energy Physics, v. 3), ed. by C. Jarlskog (World Scientific, Singapore, 1988), also available as SLAC-PUB-4476 (1987); see Ref. 5 for additional references.
8. M. Kobayashi and T. Maskawa, *Prog. Theor. Phys.* **49**, 652 (1973).
9. R. Aleksan, J. Bartelt, P. R. Burchat and A. Seiden, SLAC-PUB-4673 (1988), to be published in *Phys. Rev. D*.
10. P. Oddone, *Proceedings of the UCLA Workshop: Linear Collider $B\bar{B}$ Factory Conceptual Design,* ed. by D. Stork, p. 243 (1987).
11. See D. Hitlin, T. Nakada and A. Sanda, these proceedings, in which it is argued that 8 GeV on 3.5 GeV is an optimum asymmetry.
12. The quantity $(t'+t)$ cannot be measured in an asymmetric storage ring running on the $\Upsilon(4S)$ because the bunch lengths are much longer than the decay lengths.
13. This number is smaller than the value of $d = 0.71$, which was used at the Summer Study, and is based on more precise subsequent work. Correspondingly, the values in Table 2 have changed somewhat from those shown in the oral report.
14. S. Stone, *Modern Physics Lett. A* **3**, 541 (1988) has studied the luminosity required to observe CP violation with this technique and has arrived at somewhat more optimistic conclusions than those in this study.
15. For an asymmetric collider operating in this region, one might want to integrate only over $(t'+t)$. The equation analogous to Eq. (4) is then

$$R(\Delta t) \propto e^{-\Gamma|\Delta t|}\left[1 \mp \frac{\sin\phi}{\sqrt{1+x^2}}\sin(x\Gamma|\Delta t| + \tan^{-1}x)\right].$$

16. W. B. Atwood, I. Dunietz and P. Grosse-Wiesmann, SLAC-PUB-4544 (1988), submitted to *Phys. Lett. B*.
17. D. Blockus *et al.*, SLAC-PROP-1 (1986).
18. G. Alexander *et al.*, CERN-88-06 (1988).
19. C. K. Sinclair, *J. Phys. (Paris)* **46**, C2-669 (1985).

20. SLD Collaboration, SLAC–273 (1984); A. Litke *et al.*, *Nucl. Instrum. Methods A* **265**, 93 (1988); G. Batignani *et al.*, INFN PI/AE 88/4 (1988); and M. Burns *et al.*, CERN–EP/88–82 (1988).
21. V. Lüth, SLAC–PUB–4553 (1988).
22. K. Wacker *et al.*, PSI report number PR–88–09 (1988).
23. N. B. Mistry, P. S. Drell and N. Katayama, these proceedings.
24. D. G. Cassel, N. B. Mistry, J. A. Mueller and N. Katayama, these proceedings.
25. C. Albajar *et al.*, *Phys. Lett.* **186B**, 247 (1987).
26. H. Albrecht *et al.*, *Phys. Lett.* **192B**, 245 (1987).
27. R. Fulton *et al.*, submitted to the XXIV International Conference on High Energy Physics, Munich, August 4–10, 1988.
28. A. A. Garren, "APIARY I Design," SLAC/AP–071 (1988). See Ref. 4 for a discussion.
29. C. Damerell, Rutherford Appleton Laboratory report RAL 86–077 (1986).
30. S. Parker, University of Hawaii report UH–511–633–88 (1988); S. L. Shapiro *et al.*, SLAC–PUB–4701 [Rev.] (1988).
31. W. B. Atwood *et al.*, *Nucl. Instrum. Methods A* **252**, 295 (1986).
32 E. Blucher *et al.*, *Nucl. Instrum. Methods A* **249**, 201 (1986).
33. At momenta of 0.8 and 1.2 GeV/c, the difference between muon and pion range is 24.6 and 18.2 g/cm^2, respectively. See W. H. Barkas and M. J. Berger, NASA SP–3013 (1964).
34. T. Nakada reached similar conclusions based on a Monte Carlo simulation of $B \to \psi K_s$ reconstruction from $B\bar{B}^*$ events, which is described in PSI internal report, PSI/TN–1/88, unpublished.