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CP VIOLATION IN THE B SYSTEM
— PHYSICS AT A HIGH LUMINOSITY B FACTORY*—

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CP Violation remains one of the unsolved puzzles in particle physics. Measurements of CP violating asymmetries in B meson decay will test the Standard Model of electro-weak interactions and tell whether this phenomenon can be explained simply through the non-zero angles and phase in the CKM matrix. A high luminosity, energy asymmetric e^+e^- storage ring provides the most versatile and best opportunity to measure CP violating effects and to test the consistency of the Standard Model, and should discrepancies occur, information will be available to establish the origin of CP violation outside the model. Such a machine is a very challenging, though technically achievable device, that when complemented with a suitable detector will represent a very exiting laboratory for studies of many aspects of beauty, charm, and $\tau^\pm$ physics in the coming decade.

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INTRODUCTION

Even though CP violation was discovered more than 25 years ago, its observation remains restricted to the neutral kaon system and its origin is still uncertain. In the Standard Model of electro-weak interactions CP violation is incorporated in a natural way in the Cabibbo–Kobayashi–Maskawa (CKM) mixing matrix for three generations:

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \quad .$$

These nine matrix elements can be expressed in terms of four independent quantities, that have been conveniently chosen by Wolfenstein[1)]:

$$V \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \quad .$$

For three generations of quarks there occurs a unique complex phase that independent of any phase convention can be taken to be

$$arg(V_{us}V_{ub}^*V_{cs}^*V_{cb}) \quad .$$

Unitarity of the CKM matrix implies that

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \quad ,$$

a relationship that can be represented geometrically by a triangle in the complex plane.[2)] One can choose to orient the triangle such that V_{cb} and V_{cd} become almost real and use the fact that $V_{ud} \simeq 1$, $V_{tb} \simeq 1$. The above relationship then reduces to

$$V_{ub}^* + V_{td} = -V_{cd}V_{cb}^* \quad ,$$

as shown in Figure 1.

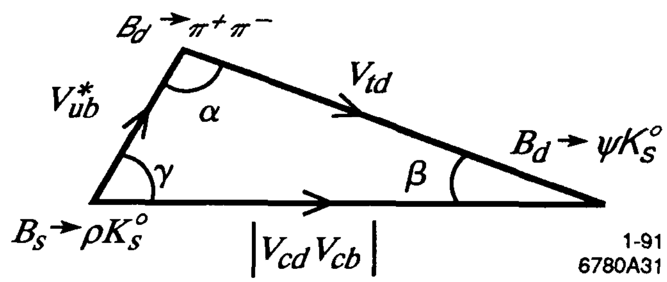

Figure 1: Graphical representation in the complex plane of the relationships between CKM elements.

The lengths of the three sides of the triangle are defined by B^0-$\overline{B^o}$ mixing (V_{td}), non-charm decays of B mesons (V_{ub}), and a combination of the B lifetime and semi-leptonic branching ratio (V_{cb}). The interior angles α, β and γ determine the CP violating asymmetries in neutral B meson decays. For different quark processes governing the decay of neutral B mesons, Table I lists the corresponding decays and the CP asymmetries in terms of these angles.

Table I. Decay modes of B_d^o and B_s^o to CP eigenstates and the interference terms which appear in the time-dependent CP-violating asymmetry.

Quark Subprocess	Decay Mode	Interference Term
$\overline{b} \to \overline{c} + c\overline{s},\ \overline{c} + c\overline{d},\ \overline{s}$	$B_d \to \psi K_S, \chi K_S, \phi K_S, \eta_c K_S,$ $\omega K_S, \rho K_S, D^+D^-, \overline{D}^0 D^0,$ $\psi K_L, \phi K_L, \rho K_L, \ldots$	$-\sin(2\beta)$
$\overline{b} \to \overline{u} + u\overline{d}$	$B_d \to \pi^+\pi^-, \overline{p}p, \rho\pi^o,$ $\omega\pi^o, \pi^o\pi^o$	$-\sin(2\alpha)$
$\overline{b} \to \overline{u} + u\overline{d}$	$B_s \to \rho K_S, \omega K_S,$ $\rho K_L, \omega K_L$	$-\sin(2\gamma)$

Within the three-generation Standard Model, the allowed ranges for the phases α, β, and γ are constrained by measurements of weak interaction couplings. Existing measurements of $|V_{cb}|$ and $|V_{ub}/V_{cb}|$ from CLEO[3)] and ARGUS[4)] provide direct information on the allowed values for CKM parameters; loop processes responsible for CP violation in K^o decays (ϵ) and B^o-$\overline{B^o}$ mixing (x_d) lead to additional constraints. The implications of the experimental data for the unitarity triangle of the triangle, are shown in Figure 2 for a top quark mass of 120 GeV/c^2.[5)] In this plot, the unitarity triangle has been renormalized such that the baseline extends from $(\rho, \eta) = (0,0)$ to $(1,0)$. The second and third sides of the triangle terminate at a point (ρ, η) in the shaded region, resulting in a range of possible values for the interior angles α, β and γ. The three angles can have any value indicated in Figure 3 as a function of the top quark mass. It is worth noting that, although 90° is not excluded for α or γ (and thus zero asymmetry), the angle β is restricted to lie between 2° and 47°.

If the phenomenon of CP violation can be explained by the Standard model simply through the non-zero angles and phase of the CKM matrix then large CP violating asymmetries are expected in the decays of neutral B mesons, and those asymmetries are precisely related to the CKM parameters. Should the measurements fail to be consistent with those relations then the origin of CP violation must lie outside the Standard Model with three generations of quarks. Other conceivable sources of CP violation are one or more additional generations of quarks and leptons, right handed weak currents, a more complicated Higgs sector, supersymmetry, or as originally proposed by Wolfenstein a new super-weak interaction.

CP violation in B decays manifest itself in a number of different ways and can be detected, at least in principle, in a variety of colliding beam or fixed target experiments with

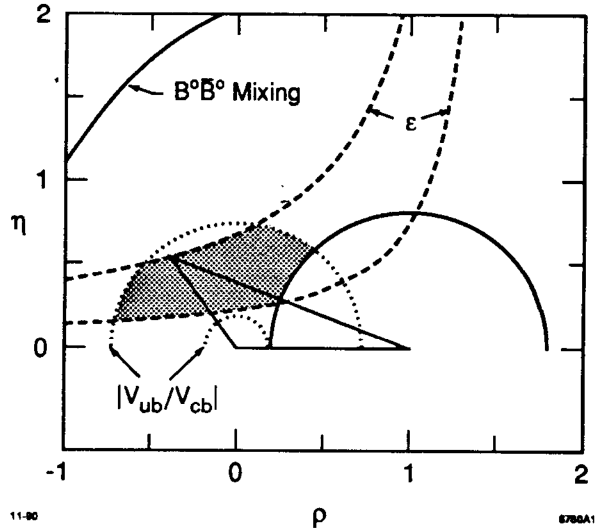

Figure 2: The allowed region (shaded) for the Wolfenstein parameters (ρ, η) given present constraints from $|V_{ub}/V_{cb}|$ (dotted), ϵ_K (dashed) and B^o-$\overline{B^o}$ mixing (solid lines) for a top quark mass of 120 GeV/c^2.

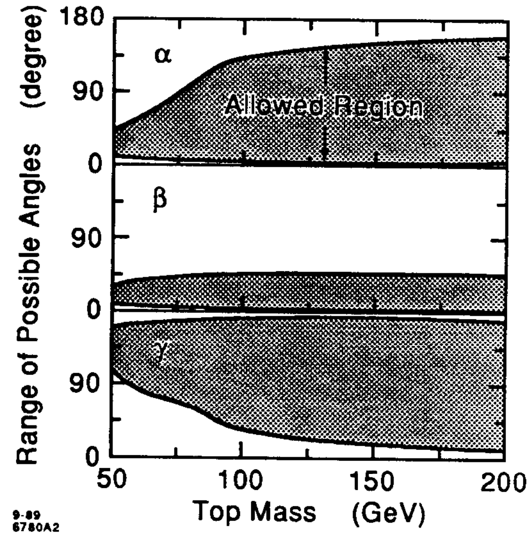

Figure 3: Projections of allowed regions for the three unitarity angles, as a function of top quark mass.

high energy photon, $e^{\pm}$, or hadron beams. B mesons are produced via electromagnetic or strong interactions in states of definite flavor (denoted by B^o and $\overline{B^o}$). These states are not necessarily the eigenstates of mass (denoted as B_1 and B_2) nor are they eigenstates of CP (denoted as B_+ and B_-). As in the neutral kaon system, CP violation can either originate in the decay amplitudes (referred to as direct CP violation) or in the mixing of B^o and $\overline{B^o}$. In the following, these possibilities and some experimental consequences will be discussed. This will be followed by a very brief summary of the parameters for a so-called B Factory, a high luminosity e^+e^-storage ring operating near threshold for $b\bar{b}$ production. The design of such a machine and the study of experiments specifically designed for measurements of CP violation have received considerable attention in recent years. Most of the material presented below has been extracted from the proceedings of numerous workshops sponsored by Frascati,[6] UCLA,[7] PSI[8] and CERN,[9] Cornell University,[10] DESY,[11,12] and SLAC,[13,14] in addition to the DPF Summer Studies at Snowmass.[15,16]

CP Mixture of the Mass Eigenstates

Since weak interaction does not conserve the beauty quantum number, the B^o and $\overline{B^o}$ can mix via second order weak transitions. The observable particles, B_1 and B_2, which have definite masses, m_1 and m_2, and obey exponential decay laws with decay widths Γ_1 and Γ_2, are linear superpositions of B^o and $\overline{B^o}$,

$$|B_i\rangle = p|B^o\rangle \pm q|\overline{B^o}\rangle \quad ,$$

where $i = 1, 2$. If these mass eigenstates are not equal mixtures of the flavor eigenstates $|\overline{B^o}\rangle$ and $|B^o\rangle$, i.e. $|q/p| \neq 1$, they are not CP eigenstates. Explicitly,

$$p = \frac{1}{\sqrt{2}} \frac{1 + \epsilon_B}{\sqrt{1 + |\epsilon_B|^2}} \qquad q = \frac{1}{\sqrt{2}} \frac{1 - \epsilon_B}{\sqrt{1 + |\epsilon_B|^2}} \quad ,$$

with $\epsilon_B \neq 0$. The mass eigenstates propagate as

$$|B_i(t)\rangle = e^{-\Gamma_i t/2} e^{i m_i t} |B_i(0)\rangle$$

and consequently the flavor eigenstates have the following time evolutions,

$$|B^o(t)\rangle = e^{-\Gamma t/2} e^{i\Delta m t/2} \left(\cos \frac{\Delta m t}{2} |B^o(0)\rangle + i\frac{q}{p} \sin \frac{\Delta m t}{2} |\overline{B^o}(0)\rangle \right)$$

$$|\overline{B^o}(t)\rangle = e^{-\Gamma t/2} e^{i\Delta m t/2} \left(\cos \frac{\Delta m t}{2} |\overline{B^o}(0)\rangle + i\frac{p}{q} \sin \frac{\Delta m t}{2} |B^o(0)\rangle \right) \quad ,$$

where $\Delta m = m_1 - m_2$, and $\Gamma = (\Gamma_1 + \Gamma_2)/2$. For $\epsilon_B \neq 0$, one expects to observe a time integrated asymmetry in the transition rates as a measure of CP violation,

$$A = \frac{\Gamma(B^o \to \overline{B^o}) - \Gamma(\overline{B^o} \to B^o)}{\Gamma(B^o \to \overline{B^o}) + \Gamma(\overline{B^o} \to B^o)} = \frac{|p|^4 - |q|^4}{|p|^4 + |q|^4} \simeq 4 Re\ \epsilon_B \quad .$$

Within the Standard Model this asymmetry is expected to be small, $A \leq 10^{-3}$.[17] This is in full analogy to the asymmetry in semi-leptonic decay of neutral kaons, where $Re\ \epsilon_K = (1.635 \pm 0.008) \times 10^{-3}$.

Experimentally, this CP asymmetry could be observed as an inequality in the like-sign di-lepton rates,

$$A = \frac{N^{++} - N^{--}}{N^{++} + N^{--}} \quad .$$

Starting at $t = 0$ with an equal number of B^o and $\overline{B^o}$, the semi-leptonic decay $B^o \to l^+ \nu X$ can be used to identify a B^o decay as distinct from a $\overline{B^o}$ decay. Other decay modes such as $B^o \to D^{*-} X$ are also suitable. The statistical error on the asymmetry is $\delta A = 1/\sqrt{N^{++} + N^{--}}$. To establish a non-zero effect to the level of s standard deviations ($s = A/\delta A$) requires a total produced $B\overline{B}$ sample of at least

$$N_{B\overline{B}} = \frac{2s^2}{\mathcal{BR}^2 A^2 \epsilon^2 r} \geq 10^{10} \quad .$$

Here we have assumed a branching ratio $\mathcal{BR}$=0.2, a detection efficiency $\epsilon = 0.5$, a minimum value of $s = 3$, and a mixing rate $r = (N^{++} + N^{--})/N^{+-} = 0.2$. However, significant backgrounds are expected from semi-leptonic decays of $B^{\pm}, D^{\pm}$ and $K^{\pm}$, and in most experiments an identification of the exclusive semi-leptonic B^o or $\overline{B^o}$ decay will be required. While the efficiency estimate may be realistic for an e^+e^- experiment, the required rate is well beyond expectations for a B Factory. In a hadronic experiment, trigger requirements and signal purity are very difficult to obtain without an enormous loss in efficiency. Thus, it is unlikely that this measurement can be performed if the CP asymmetry is as small as predicted in the Standard Model.

Direct CP Violation

If there are weak decay amplitudes that violate CP, then one expects to observe time-integrated asymmetries in flavor specific decays of both neutral and charged B mesons. When two different amplitudes contribute to the decay of a B meson to a final state f, the amplitude for the decay can be written as

$$\langle f|\mathcal{L}(\Delta B=1)|B\rangle = M_1\ e^{i\alpha_1+i\phi_1} + M_2\ e^{i\alpha_2+i\phi_2} \quad .$$

M_1, M_2 denote the matrix elements with the CKM phases ϕ_1, ϕ_2 and the strong (or electromagnetic) phases α_1, α_2. The amplitude of the CP conjugate decay $\overline{B} \to \overline{f}$ reads

$$\langle \overline{f}|\mathcal{L}(\Delta B=1)|\overline{B}\rangle = M_1\ e^{i\alpha_1-i\phi_1} + M_2\ e^{i\alpha_2-i\phi_2} \quad ,$$

where the CP invariance of the strong interaction fixes the phase shifts. A difference in rate for the two processes establishes CP violation, and we have

$$\begin{aligned} A &= \frac{\Gamma(B\to f)-\Gamma(\overline{B}\to\overline{f})}{\Gamma(B\to f)+\Gamma(\overline{B}\to\overline{f})} \\ &= \left(\frac{2M_1M_2}{M_1^2+M_2^2}\right)\frac{\sin(\alpha_1-\alpha_2)\ \sin(\phi_1-\phi_2)}{1+2M_1M_2/(M_1^2+M_2^2)\cos(\phi_1-\phi_2)\cos(\alpha_1-\alpha_2)} \quad . \end{aligned}$$

This asymmetry can only be sizable if the two interfering amplitudes

— are comparable in magnitude,

— have a non-trivial strong phase shift, $\alpha_1-\alpha_2\neq 0$, and

— have a relative complex weak phase, i.e. $\phi_1-\phi_2\neq 0$.

It turns out that processes that fulfil these conditions involve at the quark level loop diagrams with a gluon or photon, usually referred to as penguin diagrams. Figure 4 shows an example for two quark processes that could lead to direct CP violation in decays such as $B^+ \to K^+\pi^+\pi^-$ or $B^o \to K^+\pi^-$. These diagrams generate an absorptive part due to on-mass-shell rescattering of a virtual gluon. At the same time, loops with contributions from different generations of quarks produce complex CKM phases. While there is agreement among theorists that rescattering is bound to occur, there are widely different opinions about the reliability of calculations of rates and asymmetries for exclusive decay modes.[18] Some theorists expect that some of these processes will show significant CP violation, possibly as

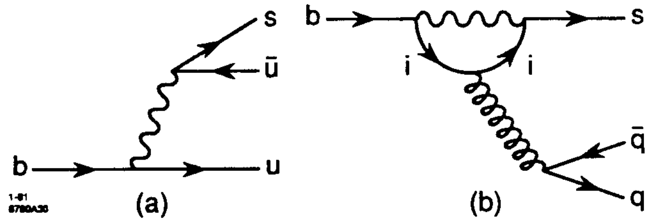

Figure 4: Quark diagrams for the process $b \to s\bar{u}u$.

high as 10% with branching ratios of the order of 10^{-5}. In non-standard models involving charged Higgs particles, asymmetries as large as 70% might occur.[19)]

From an experimental point of view, there are several advantages to the search for CP violation in these processes. First, most of the decay modes result in rather simple, charmless final states with relatively good detection efficiencies. Secondly, the flavor identification is obvious in both charged and neutral decays, and thus the measurement of the asymmetry does not require vertex detection or tagging of the second B decay. This opens the possibility that these effects might be detectable in hadronic experiments where production rates of B mesons are very large. However, to produce a convincing effect, the experimenters will have to make sure that B and $\overline{B}$ are produced in equal numbers and that the detector has equal sensitivity to the two charge-conjugate states. The total number of $B\overline{B}$ events needed to establish an effect with a statistical significance of s standard deviations is

$$N_{B\overline{B}} = \frac{s^2}{\mathcal{BR} A^2 \epsilon} \geq 4 \times 10^6 \quad ,$$

provided there is at least one decay mode with $\mathcal{BR}\,\epsilon = 10^{-5}$ and $A \geq 0.5$. To extract information about the parameters of the quark mixing matrix from a this asymmetry measurement, one needs to know not only the amplitudes M_1 and M_2, but also the hadronic phase shift $\Delta\alpha = \alpha_1 - \alpha_2$. It has been recently suggested[20)] that in three body final states a detailed analysis of the Dalitz plot could permit the selection of events with maximum asymmetry, i.e. $\Delta\alpha = 90^o$.

Time-Dependent CP Asymmetries

The complications that are expected to affect the asymmetry measurement described above can be avoided in the study of the interference of two amplitudes of comparable magnitude that result from $B^o - \overline{B^o}$ mixing. In particular, such measurements permit a clean interpretation in terms of the CKM matrix elements and thereby represent a sensitive tests of the Standard Model. "Clean interpretation" means that the measured value of the asymmetry can be related to the CKM parameters without significant hadronic corrections or other

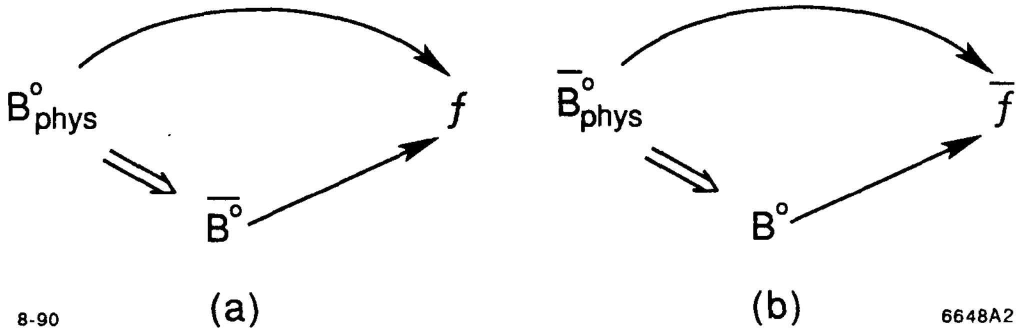

Figure 5: Illustration of the two transition amplitudes from $B^0(\overline{B^o})$ to the final state $f(\overline{f})$ via mixing to $\overline{B^o}(B^o)$ or direct.

uncertainties. Two ingredients are essential for this: First, the difference in width between the two mass eigenstates must be much smaller than the difference in mass, $\Delta\Gamma \ll \Delta m$. Second, the decay has to be dominated by a single amplitude. As illustrated in Figure 5, this means that the asymmetry is the result of interference between the direct transition $B^o \to f_{CP}$ and the transition involving mixing, $B^o \to \overline{B^o} \to f_{CP}$. Under these conditions, the asymmetry depends only on the type of the decaying B meson, B_d or B_s, and the quark subprocess involved in the decay. Examples of suitable decay modes are listed in Table I.

If B^o and $\overline{B^o}$ decay to same final state f, and if f is an eigenstate of CP, with eigenvalue η_f, then

$$CP|f\rangle = \eta_f |f\rangle \quad .$$

Furthermore, if the decay is dominated by a single amplitude w_f, then:

$$\frac{\overline{w}_f}{w_f} = \eta_f e^{-2i\phi_f} \quad ,$$

where the phase ϕ_f depends only on CKM elements. In this case, the mass eigenstates are eigenstate of CP, with $|p/q| = 1$ in the earlier notation, and the CP violation comes about because of the relative phase in the transition amplitudes. For decay modes involving $c\overline{c}$, like ψK^o_s or D^+D^-, we have

$$\phi_f = \beta = arg(V_{cd}V^*_{cb}/V_{td}V^*_{tb}) \quad ,$$

and for charmless modes, such as $\pi^+\pi^-$, we have

$$\phi_f = \alpha = arg(V_{ud}V^*_{ub}/V_{td}V^*_{tb}) \quad .$$

The common denominator $V_{td}V^*_{tb}$ comes from the box diagram for the $B^o\overline{B^o}$ mixing, the nominator originates from the b decay diagram.

Starting with an initially pure $B^0(\overline{B^o})$ state, the time-evolved decay rates to the CP eigenstate f $(\eta_f = +)$ are:

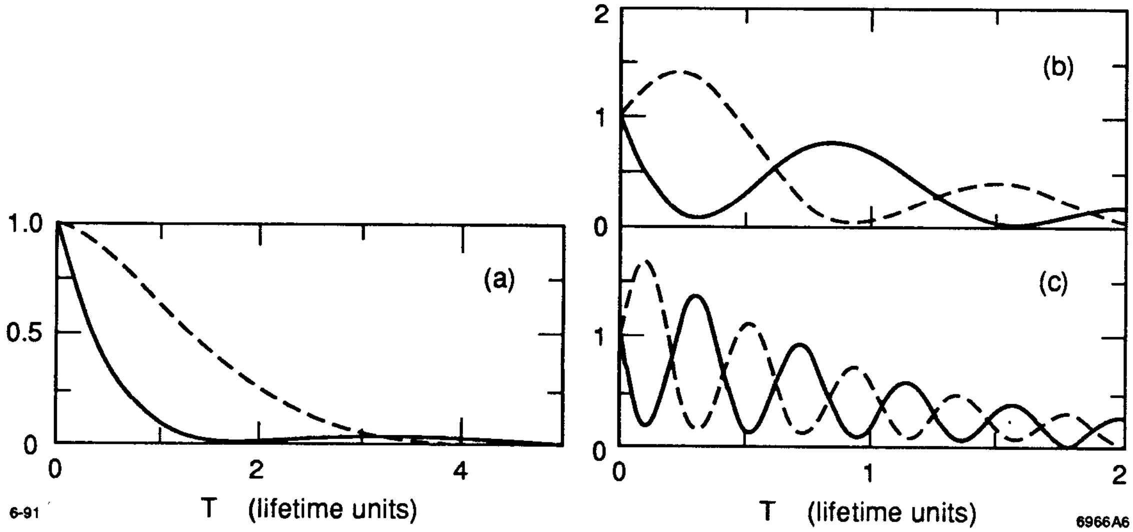

Figure 6: Time-dependent decay rate for $B^o_{phys} \to f$ (solid line) and for $\overline{B^o}_{phys} \to f$ (dashed line) for $\mathrm{Im}\lambda = 0.88$ and three different mixing rates $x = \Delta m/\Gamma$, namely a) $x = 1.0$, b) $x = 5.0$, and c) $x = 15.0$.

$$\Gamma(B^0_{phys} \to f) \propto e^{-\Gamma t}[1 - \mathrm{Im}\lambda \sin(\Delta m t)] \quad ,$$

$$\Gamma(\overline{B^o}_{phys} \to f) \propto e^{-\Gamma t}[1 + \mathrm{Im}\lambda \sin(\Delta m t)] \quad ,$$

where the amplitude for CP-violation is $\mathrm{Im}\lambda = -\sin 2\phi_{\mathrm{f}}$, and $\Delta m = m_1 - m_2$ is the mass splitting between the two neutral B meson mass eigenstates. The interference term $\mathrm{Im}\lambda \sin(\Delta m t)$ is non-zero

— if the B^o and $\overline{B^o}$ mix due to $\Delta m \neq 0$, and

— if $\mathrm{Im}\lambda \neq 0$, a condition that in the context of the Standard Model is satisfied for three or more generations.

The sign of the interference term depends on the flavor of the B meson, and also on the time of the decay. Thus, in experiments with equal production of B^o and $\overline{B^o}$ or equal mixtures of $CP = +1$ and $CP = -1$ final states the average asymmetry vanishes. Likewise, under certain conditions the time integrated asymmetry may be strongly diluted. This is illustrated in Figure 6, where the time dependence of the decay rates is given for a value of $\mathrm{Im}\lambda = 0.88$ and three different values of $x = \Delta m/\Gamma$. The lowest value of $\Delta m/\Gamma$ corresponds to that measured for $B_d\overline{B}_d$ mixing; the other two are chosen to be in the range expected for $B_s\overline{B}_s$ mixing.

In practice, several methods to measure the asymmetry can the applied, depending on the particular experiment.[21] For example, at the $\Upsilon(4s)$, the events can be divided into four classes, depending on the time-order of the tagging and CP decays:

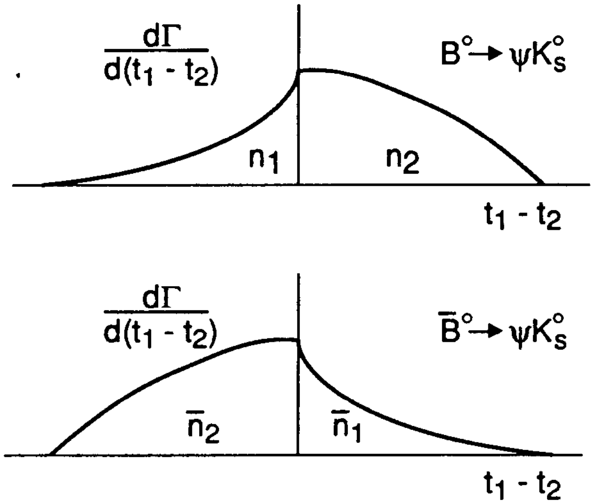

Figure 7: Separation of events into classes with positive and negative CP interference, depending on time order of the two decays.

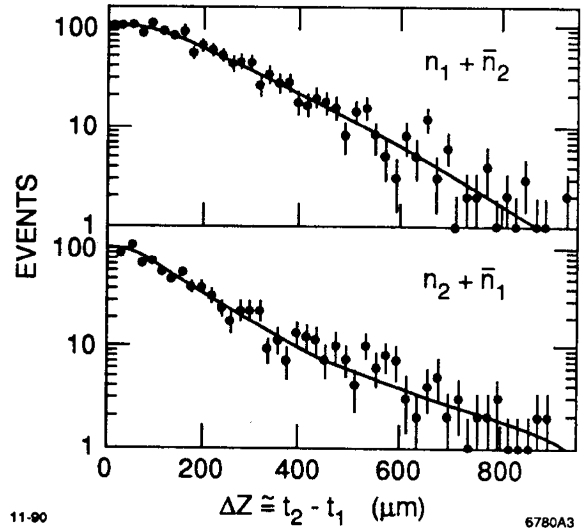

Figure 8: Example of a fit to the distribution of longitudinal vertex separation Δz between two decay vertices. The statistics corresponds to 2300 tagged decays.

$$t_{\rm CP} < t_{tag} \quad \begin{cases} N_1: & B_{tag} = B^0 \\ \overline{N}_1: & B_{tag} = \overline{B^o} \end{cases} \qquad t_{\rm CP} > t_{tag} \quad \begin{cases} N_2: & B_{tag} = B^0 \\ \overline{N}_2: & B_{tag} = \overline{B^o} \end{cases}$$

Interference in the partial rates for the four classes is illustrated conceptually in Figure 7. Taking appropriate sums and differences of the observed numbers of events, a non-zero asymmetry can be measured:

$$A_{\rm CP} = \frac{(N_1 - \overline{N}_1) - (N_2 - \overline{N}_2)}{N_1 + \overline{N}_1 + N_2 + \overline{N}_2} = -d_0 \sin 2\phi \quad ,$$

with an effective dilution factor $d_0 = x_d/(1+x_d^2) \simeq 0.47$. A more sensitive technique is to fit the distribution of vertex separation Δz, after division into classes with positive $(N_1 + \overline{N}_2)$ and negative $(\overline{N}_1 + N_2)$ interference. The dilution factor then becomes $d_0 \simeq 0.58$ (Figure 8).

Extension of the measurement to other decay modes

The requirement that the final state be a pure CP eigenstate can be relaxed and measurements of CP violation can be extended to many other decay modes, without sacrificing the predictability of the asymmetry which is a key component in using B decays for a precision test of the Standard Model. A summary of possible extensions and a list of final states is given in Table II. Specific examples for the analysis of CP mixed states are given below.

Many decay modes of the B^0 involving three particles, or two particles with spin, are mixtures of different CP eigenstates. Therefore the measured CP asymmetry will depend on

Table II: B decays suitable for the study of mixing-induced CP violation (from Ref 14).

.	Class	Examples
1.	$B^0 \to f$, $\overline{B^o} \to f$ where f = CP Eigenstate	ψK^o_S $\pi^+\pi^-$ D^+D^-
2.	$f = (A)_{CP}(B)_{CP}$ or $A\overline{A}$ where A, B have spin	$\psi\rho^0$ $D^{*+}D^{*-}$
3.	$f = (A)_{CP}B$ where $B \to (C)_{CP}$	$\psi K^{*o}, K^{*o} \to K^o_S\pi^0$ $\overline{D^o}\pi^0$, $\overline{D^o} \to \pi^+\pi^-$
4.	f = 3-body state (a) CP Eigenstate (b) Mixture of CP States	 $\eta_C K^o_S\pi^0$ $\psi K^o_S\pi^0$
5.	$f = A_1\overline{A}_2$ where $A_1\overline{A}_2 = (q_x\overline{q}_y)(\overline{q}_x q_y)$ (CP self-conjugate set of quarks)	$d\overline{d}c\overline{c} \equiv D^{*+}D^-$ $d\overline{d}s\overline{s} \equiv K^{*o}\overline{K^o}$ $d\overline{d}u\overline{u} \equiv \rho^\pm\pi^\mp$, $a_1^\pm\pi^\mp$

the ratio of CP-even and CP-odd states. The decay rate of a state that evolved from an initially pure $B^0(\overline{B^o})$ to the final state $f(\overline{f})$ can be written in the form

$$\Gamma(B^0_{phys} \to f) = \Gamma_+(1+a) + \Gamma_-(1-a) \quad ,$$

$$\Gamma(\overline{B^o}_{phys} \to \overline{f}) = \Gamma_+(1-a) + \Gamma_-(1+a) \quad .$$

The CP-even and CP-odd rates are denoted by the widths Γ_+ and Γ_-, respectively. The rates are time dependent and Γ_+ and Γ_- contain a factor $e^{-\Gamma t}$, where Γ is the average width of the B^0 mass eigenstates.

The measured asymmetry is

$$A \equiv \frac{\Gamma(B^0_{phys} \to f) - \Gamma(\overline{B^o}_{phys} \to \overline{f})}{\Gamma(B^0_{phys} \to f) + \Gamma(\overline{B^o}_{phys} \to \overline{f})} = -\mathrm{Im}\lambda \sin(\Delta m t)\, \frac{\Gamma_+ - \Gamma_-}{\Gamma_+ + \Gamma_-} \quad .$$

The last factor gives the dilution that occurs if the final state f is a mixture of CP-even and CP-odd parities. If an analysis of angular distributions can be made for each time-bin separately (since the asymmetry is different at different times) this dilution can be avoided, regardless of the Γ_+/Γ_- ratio.

Several methods can be used to reconstruct CP eigenstates from a superposition of helicity states. The simplest analysis is based on a quantity called transversity, which characterizes the spin projections of a three body state in the direction transverse to the momentum plane.[22] This approach has the advantage that the analysis can be performed with the combined sample of resonant and non-resonant contributions to a given final state, whereas the more detailed partial wave analysis requires reconstruction of specific two-body resonances.

In a three-body decay, such as $B^o \to \psi K_S^o \pi^o$, the three final-state momenta define a plane and are invariant under reflections in this plane, which can be expressed as $R_{xy} \equiv P e_{i\pi J_z}$. In fact, for any $J = 0$ state the following relations hold,

$$CP|J=0\,\rangle = CR_{xy}|J=0\rangle \equiv CPe^{i\pi J_z}|J=0\,\rangle = (CP)_{int} \cdot e^{i\pi\tau}|J=0\,\rangle \quad ,$$

here J_z is the projection of the total angular momentum on the z axis and τ denotes the sum of the transversities of the three particles, i.e. the projection of the total spin angular momentum of the state on the z axis. The equality follows because all three momenta in the centre-of-mass system remain invariant under R_{xy} and therefore only the internal degrees of freedom contribute. The relation applies to any three-body or quasi-three-body state with a well defined $(CP)_{int}$.

For the final state $\psi K_S^o \pi^o$ with $(CP)_{int} = -1$, we have $CP = -1$ for $\tau = 0$, and $CP = +1$ for $\tau = \pm 1$. The two CP states can be distinguished by the angular distribution of the lepton pairs from the decay $\psi \to \ell^+\ell^-$ relative to the momentum of the ψ. In fact, the ARGUS collaboration has shown that inclusive ψ from B decays in the two-body momentum interval are strongly polarized. A fit of the form $1 + \alpha \cos^2\theta_{\ell^+}$ to the distribution of the angle θ_{ℓ^+} between the lepton direction and the ψ boost direction in the ψ rest frame gives $\alpha = -1.17 \pm 0.17$. This means that the state is dominated by $\tau = 0$, i.e. the state has $CP = -1$. [23] Consequently the dilution of the asymmetry is small, and the sensitivity of the decay $B^0 \to \psi K^{*0}$ is expected to be comparable to that for the decay $B^0 \to \psi K_S^o$.

The final state $D^{*+}D^{*-}$ contains several partial waves and can have $CP = +1$ and $CP = -1$. Since the total angular momentum has to be J=0 for the decay of a spinless particle, $L = S$ for the orbital angular momentum, and the CP eigenvalue for this state equals P, the parity eigenvalue. Since the intrinsic parity of the $D^{*+}D\pi$ system is $P = -1$, it follows that the CP eigenvalue for the whole system is $CP = -1$ if $\tau = 0$ for the D^{*+}, and $CP = +1$ for non-zero transversity, $\tau = \pm 1$.

Even though one can use the transversity analysis to measure the mixture of the CP eigenstates in a given decay mode, the error for a mixed sample is always larger than for a pure sample. Figure 9 shows the increase in the error on the CP violating asymmetry as a function of the mixture for two decay modes.[24] The final state $D^{*+}D^{*-}$ is less sensitive to the mixture than the state ψK^{*o}, but based on the ARGUS measurement we already know that this state is dominantly in a $CP = -1$ state.

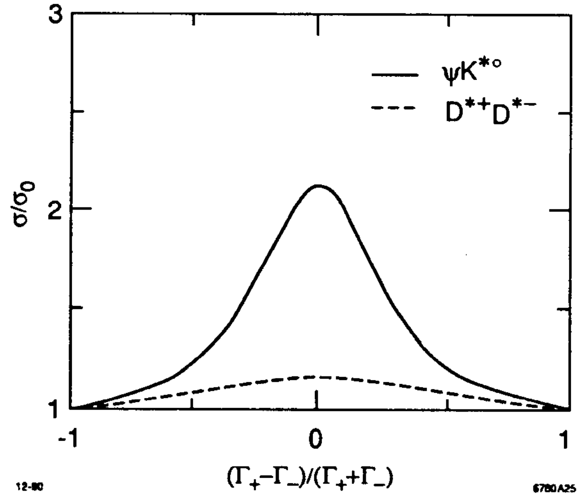

Figure 9: Increase in the uncertainty of the CP violating asymmetry as a function of the CP mixture in the decays ψK^{*0} and $D^{*+}D^{*-}$.

MEASUREMENT OF THE TIME DEPENDENT ASYMMETRY

The measurement of the time-dependent asymmetry

$$A \equiv \frac{\Gamma(\overline{B^o}_{phys}(t) \to f) - \Gamma(B^o_{phys} \to f)}{\Gamma(\overline{B^o}_{phys}(t) \to f) + \Gamma(B^o_{phys} \to f)} = \mathrm{Im}\lambda \sin \Delta m t$$

requires the following:

— First and above all, the cross section for B meson production has to be sizable. The largest cross sections for $b\bar{b}$ production are expected in hadronic interactions at high energy, i.e. either in fixed target or collider experiments. In e^+e^-annihilation, the largest rates are found at the Z^o resonance (6.3 nb) or at the $\Upsilon(4s)$ resonance (1.2 nb).

— Second, the decay of a B^o meson to a CP eigenstate has to be reconstructed with very low background. This is done best at the $\Upsilon(4s)$, where the exclusive $B\overline{B^o}$ final states not only reduce the combinatorial background, but also allow for kinematic constraints on the energy and momentum of the reconstructed B meson.

— Thirdly, the flavor of one B meson has to be tagged while the decay rate of the other to a CP eigenstate is determined.

The flavor of a neutral B meson can be derived from the presence of either a lepton from a semi-leptonic decay or a charged kaon from the secondary decay of a charm meson. In both cases the charge of the particles tags the B flavor, i.e. e^+, μ^+, and K^+ tag a B^o, and e^-, μ^-, and K^- tag a $\overline{B^o}$. The tagging quality is characterized by two quantities, the efficiency, ϵ_{tag}, which is defined as the fraction of B mesons that is tagged, and w, the fraction of all tagged events that is tagged correctly. Monte Carlo simulations indicate that for an e^+e^-experiment typical values of $\epsilon_{tag} = 0.12(0.33)$ and $w = 0.04(0.15)$ can be obtained for lepton (kaon) tagging signals.

At the $\Upsilon(4s)$ resonance, the B flavor is tagged at the time of the flavor specific decay, and the rate asymmetry needs to be measured as a function of the time difference between the two decays, $\Delta t = t_{CP} - t_{tag}$. Δt is positive if the decay to the CP eigenstate happens last, and negative if it happens first. Thus it is not only important to tag the flavor of the tagging decay but also to measure the temporal order of the decay, i.e. the sign of Δt. However, at a storage ring with equal beam energies, the $\Upsilon(4s)$ resonance is stationary in the detector, and Consequently the B decay length is typically 20 μm, much too short to be measured. This difficulty can be overcome in an asymmetric storage ring, were the e^+ and e^- collide head-on with different energies. As a result, the B^o and $\overline{B^o}$ move almost parallel to the direction of the high energy beam, and the difference in decay time can be extracted from the difference between the two decay vertices along the beam direction,

$$\Delta t \simeq \Delta z / \beta\gamma c \quad .$$

For a fixed resolution in Δz, a larger asymmetry in the beam energies will lead to a smaller fractional error on Δt. However, a larger boost will also lead to lower efficiency for the detection of secondary particles, because the size of the blind region around the beam pipe is fixed. The measurement of the asymmetry can be performed as long as the resolution in Δt is small compared to the period of the oscillation of the asymmetry. A machine with energies of 9.0 GeV and 3.1 GeV produces a boost of $\beta\gamma = 0.5$ and results in an average decay distance of 190 μm. This is sufficient for the measurement of the asymmetry in B_d^o decays, assuming that a resolution of 50–80 μm can be obtained. Monte Carlo studies show that for most CP decays the resolution in Δz is dominated by the uncertainty in the tagging vertex which is typically 45–60 μm. Thus, an asymmetric machine maintains all the advantages of operation at the $\Upsilon(4s)$ resonance and adds the ability to measure time dependent effects in B decay. Furthermore, the spatial separation of the decay vertices can also be used to associate tracks from the same B decay, thus reducing combinatorial background due to tracks from the other B decay.

While at the $\Upsilon(4s)$ $B^o\overline{B^o}$ pairs are produced in a $CP = -1$ state, above the threshold for $B\overline{B}^*$ production, the decay to $B\overline{B}\gamma$ leads to $B\overline{B^o}$ pairs in an $L = 0$, $CP = +1$ state. The tagged partial widths in this case depend on the sum of the decay times, $t_{CP} + t_{tag}$, and therefore there is no need to measure decay times. The time-integrated asymmetries are non-zero, with a dilution factor is $d_0 = 2x_d/(1 + x_d)^2 = 0.63$. The separation of the two CP states can be achieved simply by kinematics and does not require the detection of the 50 MeV photon. However, recent measurements of the $B\overline{B}^*$ cross section by the CLEO collaboration indicate that the $B\overline{B}$ rate is a factor of seven below that at the $\Upsilon(4s)$.[25] This loss in rate clearly outweighs the advantage that the $CP = +1$ sample does not have to be time sorted, and that the detector and machine can be kept symmetric.

At the Z^o resonance, the cross section is sizable for all B hadrons. However, one loses all the advantages of the $\Upsilon(4s)$ resonance, and has to deal with effects of incoherent production of $B\overline{B}$ mesons and large combinatorical background in high multiplicity hadronic states, dilution of the tagging particle by mixing, etc. The higher momenta of the B mesons leading to longer decay lengths and less multiple scattering are a definite advantage, and thus they may permit a measurement of the individual B meson lifetimes, as well mixing and for very large statistics possibly CP violation in B_s decays.

It is not totally improbable that first evidence for CP violating effects may be found in experiments using hadron beams. This is particularly likely if direct CP violation in the decay amplitude exists at a significant level. In the past, measurements based on inclusive leptons at moderate to high transverse momentum have lead to the first evidence for mixing in the B system, and similarly decay modes with unique signatures, such a ψK_S^o, are expected to lead to relatively clean, large samples of B mesons, given the large production cross section and expected increases in luminosity of the Tevatron. The addition of silicon vertex detectors will further enhance the detection efficiency and substantially reduce the background. It remains to be seen how well B decays can be tagged, and thus how large the dilution of the asymmetry will be, taking into account mixing, multiple $b\bar{b}$ production, and incorrectly tagged events.

Table III. Comparison of rates for the detection of tagged $b\bar{b}$ events and the decay $B^o \rightarrow \psi K_S^o$ at four different storage rings.

Year	1992	1991/92	199?	199?
	Tevatron	LEP	$\Upsilon(4s)$	$\Upsilon(4s)+$
c.m. Energy [GeV]	2000	91	10.58	10.63
Luminosity [$10^{30}\ cm^{-2}\ s^{-1}$]	2	16	3000	3000
Cross section, $\sigma_{b\bar{b}}[nb]$	20×10^3	6.3	1.2	0.16
$b\bar{b}$ fraction, f_b	0.0004	0.20	0.25	0.05
Efficiency $\epsilon(\psi K_S^o)$	0.05	0.46	0.58	0.58
Efficiency ϵ_{tag}	0.01	0.18	0.45	0.45
No. of events $/10^7 s$	≈ 10	4	500	80

Table III shows a comparison of projected rates and detection efficiencies for the $B^o \rightarrow \psi K_S^o$ decay in experiments at different storage rings. At the existing machines, LEP and the Tevatron, the luminosities are expected to increase and during the coming years sizable samples of events will be recorded. Experiments at e^+e^-machines will undoubtedly remain limited by statistics for several years, as long as luminosities will remain $1-2$ orders of magnitude lower than those proposed for B Factories. However, at e^+e^-machines, the experimental conditions are much less difficult and experiments are expected to continue to compete very favourably with hadron machines. At future B Factories, quantitative studies of CP violating effects require clean signal events with well defined quantum numbers in a variety of different decay modes. This appears to be a straightforward extrapolation from present experience. Furthermore, the low level of the background allows for rather simple data selection, and the simplicity of the hadronic final states permits a thorough study of the composition of the background, in particular for the tagging signal. The selection of the center-of-mass energy for a B Factory has been the subject of many workshops, and widely supported conclusion has been that operation at the $\Upsilon(4s)$ resonance is the best choice, except for the study of B_s decays.

In Table IV some of the relevant decay modes and their efficiencies for reconstruction and tagging are listed. Based on a data sample for an integrated luminosity of 30 fb^{-1} and current estimates for the branching ratios, the experimental errors on sin2α and sin2β have been estimated. The results show that with such a sample a non-zero asymmetry can be established with a significance of three standard deviations over most of the available range for these two angles.

Table IV. Summary of the branching ratios, estimated efficiencies and sensitivities for representative decay channels which can be used to determine the unitarity angles. The tagging efficiency based on leptons and kaons is taken to be 45%. For an integrated luminosity of 30 fb^{-1}, the combined errors from the quoted channels would be about ±0.06 and ±0.086 for sin2α and sin2β (from Ref. 16).

Mode	Assumed B Branching Fraction	Decay Branching Fraction	Reconstruction Efficiency	No. of Events	Error $\sigma(\sin 2\phi)$ (30 fb^{-1})
$B^0 \to \psi K_S$	7.4×10^{-4}	7.0×10^{-2}	0.58	487	0.077
$\to D^+D^-$	6×10^{-4}	1.5×10^{-2}	0.46	144	0.14
$\to \psi \overline{K}^{*o}$	12.5×10^{-4}	3.6×10^{-2}	0.30	105	0.17
$B^0 \to \pi^+\pi^-$	2×10^{-5}	1.0	0.45	142	0.18
$\to \rho^\pm\pi^\mp$	6×10^{-6}	1.0	0.48	464	0.12
$\to a_1^\pm\pi^\mp$	6×10^{-5}	0.5	0.42	207	0.18

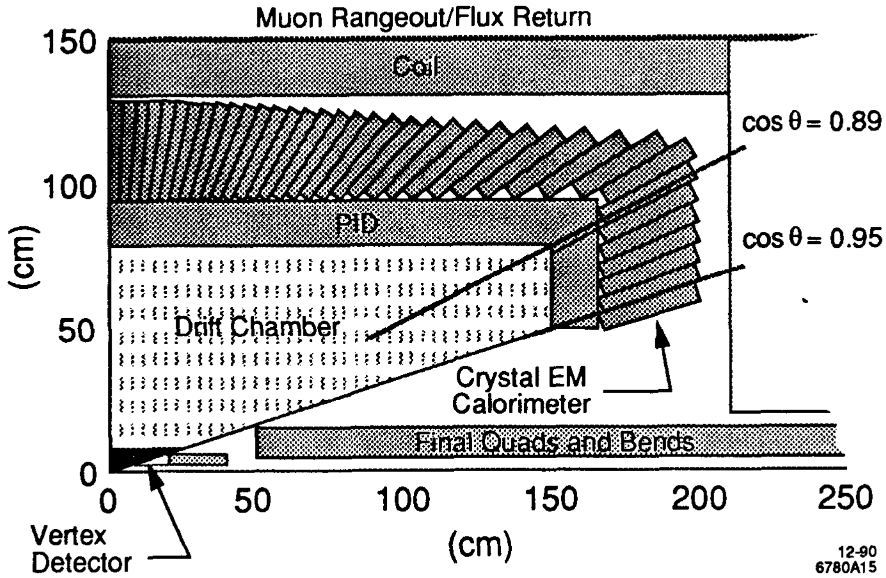

Figure 10: Layout of a detector for an asymmetric e^+e^- B Factory.

Detector for an Asymmetric B Factory

The design of a detector for an asymmetric $\Upsilon(4s)$ collider can be based on accumulated experience with detectors presently operating at the e^+e^-storage rings DORIS and CESR. Three novel features are needed: (a) solid angle coverage in the forward direction, (b) the detection of separate vertices along the beam direction, and (c) lepton detection and hadron identification up to 4.5 GeV/c momentum. A sketch of a detector layout is given in Figure 10. This layout was composed at the B Factory Workshop at SLAC, and many of the parameters were derived from the CLEO II detector now operating at CESR. Starting from the outside, the detector components and some of their specifications are listed below:

— The detection of $\mu^\pm$ with momenta as low as 0.5 GeV/c greatly enhances the efficiency for flavor tagging and ψ reconstruction. Below 1.2 GeV/c, the difference in the range between pions and muons permits a good separation. Thus a detector composed of thin tracking chambers sandwiched between iron absorber plates of about 1 cm thickness could be very effective. For higher momenta, thicker plates on the outside could be used to absorb strongly interacting pions and kaons.

— A solenoidal magnet, 3 m–4 m long, supplies a field of 1 Tesla, high enough to permit good momentum resolution and low enough to prevent too many low momentum particles from curling in the detector.

— The primary task of the electromagnetic calorimeter with good photon resolution from 10 MeV to 4 GeV is to identify electrons and to enhance the reconstruction of π^o and η^o from B, D, K^o_S, and $\tau^\pm$ decays. It also will play a crucial role in Υ spectroscopy. The goal is to achieve an energy resolution of $\sigma_E/E = 0.02/\sqrt[4]{E(\text{GeV})} \oplus 0.01$ and an angular resolution of 5–10 mrad. These specifications narrow down the choice to two techniques, a liquid krypton calorimeter or a hermetic array of CsI crystals. The cryogenic calorimeter is favoured by its radiation hardness, ease of calibration and cost. Its major disadvantages are the slow charge collection, limited hermiticy, and the total thickness of its cryostat walls. A crystal calorimeter segmented into about 10,000 elements has excellent time resolution. It is the favoured choice, in spite of its cost, sensitivity to radiation, and need for constant calibration and monitoring. A major consideration remains the degradation in performance due to material in front, primarily the particle identification system and the drift chamber cables and walls in the forward section.

— The separation of pions from kaons is essential both for the selection of exclusive B and D decays and for the tagging the flavor of the second B meson by the identification of a kaon of specific charge. $K^{\pm}$ mesons from B decays have an average momentum of 0.85 GeV/c; for exclusive two-body decays, like $B^0 \rightarrow K^+\pi^-$, the momentum spectra extend from 1.5 to 4.5 GeV/c. techniques that represent more or less viable options for particle identification at a B Factory: precision time-of-flight (TOF), dE/dx measurements in the tracking chamber, and Čerenkov counters. The predicted π/K separation as a function of momentum is shown in Figure 11 for these different devices. Part of the difficulty in finding a suitable device is the small radius dictated by the cost of the calorimeter. It not only limits the flight time, but also the number of dE/dx samples in the drift chamber. The leading contenders for hadron identification are Čerenkov counters, based on either threshold or ring imaging techniques. Their primary advantages are (a) the excellent hadron separation over the full momentum range, and (b) their modular design. Conversely, these Čerenkov devices are more challenging to construct and operate, they also add substantial amounts of material in front of the e.m. calorimeter. Recently, threshold counters composed of thin-walled double cells filled with aerogel of different density have been under study. Densities can be varied in the range 3–600 mg/cm^3, corresponding to indices of refraction between 1.0006 and 1.126. Aerogels can be doped with wavelength shifters to match the photon spectrum to the sensitivity of the photo-triode or single photon avalanche diode read-out. As with most Čerenkov counters, the primary problem is the small number of photo-electrons placing high demands on the light collection efficiency.

— Excellent momentum resolution down to very low momenta is a very powerful tool for the isolation of exclusive decay modes. A typical charged particle tracking system consists of several components, a central drift camber, a silicon vertex detector, and possibly an intermediate wire chamber. The main drift chamber has a relatively small

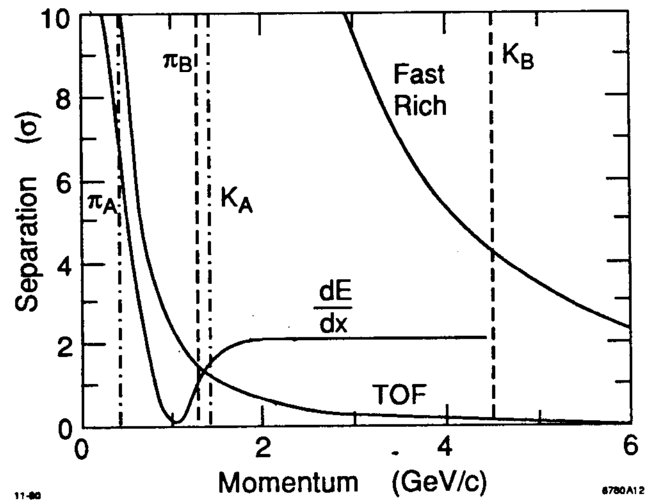

Figure 11: Predicted π/K separation as a function of the particle momentum for different devices: (a) TOF system at 1.1 m with a resolution of $150ps$ folded in quadrature with a 50 ps uncertainty due to the bunch length; (b) dE/dx for 60×1 cm samples in a drift chamber filled with a He based gas mixture; (c) a fast RICH counter, with a 1 cm thick NaF radiator and a $CsI/TMAE$ cathode; and (d) a double cell aerogel threshold Čerenkov counter with indices of refraction of $n = 1.006$ and 1.06.

radial extent (60 cm–70 cm) and can therefore only accommodate 40 layers of sense wires. To reduce the multiple scattering, helium based gases and aluminium or magnesium wires are being considered. A mixture of 85% He, 10% CO_2 and 7% iso-C_4H_8 has a factor of eight longer radiation length, substantially smaller drift velocity and smaller Lorentz angle, but pulse heights comparable to those observed in argon based mixtures. In addition, the interaction rate for synchrotron photons is about a factor of four lower in He gas.

— The primary task of the vertex detector is to measure Δz, the longitudinal distance between the decay points of the two B mesons to detect the time dependence of the CP asymmetries. It will also help to reduce the background for flavor tagging. A finely segmented, multi-layer silicon detector can provide a high precision measurement of the impact parameter, b_z parallel and b_{xy} transverse to the direction of the beam, and the angles, the azimuth ϕ and the polar angle θ, of charged particle tracks close to the beam-beam interaction point, and can thereby complement the angle and momentum measurement in the central tracking chamber. Placed on the outside of a vacuum pipe made of 1 mm thick beryllium with a radius of 25 mm, a silicon vertex detector with three or more layers can measure impact parameters of charged particles of 1 GeV/c momentum to an accuracy of 50 μm or better over a large fraction of the solid angle. An angular resolution is of 2 mrad or better in azimuth and polar angle can be achieved with double-sided strip read-out or pixel arrays of 50 μm strip pitch or pixel size. The development of low power, low noise, high density amplifier and read-out circuits needs to be pursued so as to fit the detectors into the limited space without loss of solid angle coverage, and without a substantial increase in multiple scattering. Techniques for cooling, precision assembly and alignment need to be developed.

In summary, the requirements on the detector are challenging, but it is believed that they can be met, given the rate of progress in the area of silicon vertex detectors and Čerenkov counters.

B Factory Machine Requirements

The basic parameters for an asymmetric e^+e^-storage ring have been studied by several groups at different laboratories. The design goal for these machines is to operate close to a maximum luminosity of 3×10^{33} cm^{-2} s^{-1} with an energy asymmetry of the two beams of about 3 to 1. The substantial increase in the peak luminosity (about a factor of 20 higher than that of any existing machine) is obtained by a large increase in the number of circulating bunches, keeping the number of particles per bunch roughly at the present level. The two beams are confined to separate vacuum chambers and lattices, except for the interaction region, where they are focussed and brought into collision by optical elements that are placed very closely to the interaction point, inside the detector. The high currents lead to potentially severe backgrounds (both from scattered beam particles and synchrotron photons) and substantial heating, and a major effort to reduce these problems is underway. The small spacing between the circulating bunches requires new trigger schemes, and for some detector elements data pipelines for intermediate storage. A list of specifications for the SLAC design of an asymmetric B Factory based on the PEP storage ring[26)] is given in Table V.

The different storage ring designs differ mostly in the size of the rings (almost all designs foresee installation in an existing machine tunnel) and the layout of the interaction region. The PEP based design at SLAC foresees head-on collisions of flat beams with magnetic separation. Such a configuration is similar to existing machines and allows for more reliable estimates of the luminosity. Its disadvantage is that the magnetic separation produces substantial synchrotron radiation. Designs at Cornell and KEK favour so-called crab crossing of flat beams which involves a non-zero crossing angle. This scheme uses auxiliary RF cavities to twist the bunches by an angle equal to the crossing angle so that they collide head-on. For this solution the beam separation involves no close-in magnets and thus produces less sychrotron radiation near the detector. This scheme represents a new and untried idea which may lead to unknown problems. High RF field are required at a place where space is at a premium and where the β functions are large. Preliminary tests of the cavity and operation with finite crossing angles are being planned.

Table V. Machine parameters of the SLAC design for an asymmetric B Factory to be installed in the existing PEP tunnel (from Ref. 26).

Parameter	High Energy Ring	Low Energy Ring	Units
Centre-of-mass energy	10.58		GeV
Beam energy	9.0	3.1	GeV
Peak luminosity	3.0×10^{33}		$cm^{-2}\ s^{-1}$
Luminosity life time	2.1		hr
Number of populated bunches	1658	1658	
Number of empty bunches	88	88	
Bunch spacing	1.26		m
Machine circumference	2199.3	2199.3	m
Circulating current	1.48	2.14	A
Number of particles/bunch	4	6	10^{10}
Natural energy spread	5.5	3.0	MeV
Horizontal spot size at IP	190	190	μm
Vertical spot size at IP	7.4	7.4	μm
Bunch length	1.0	1.0	cm

Conclusions

CP violation has been one of the unsolved puzzles in particle physics, and until we will be able to confront the Standard Model with measurements of CP violating asymmetries in B decay, this puzzle will continue to exist. Experiments at an asymmetric e^+e^-- storage ring operating at the $\Upsilon(4s)$ are best suited to test the Standard Model predictions by measuring the time-dependent asymmetries in B_d decays from which the unitarity angles α and β can be extracted. With a data sample corresponding to an integrated luminosity of 30 fb^{-1} and current estimates for the branching ratios, the expected experimental errors on sin2α and sin2β are such that a non-zero asymmetry could be established with a significance of three standard deviations over most of the available range for these two angles.

The measurement of the third angle of the unitarity triangle, γ, requires a sample of $B_s^o\overline{B}_s^o$ that can be obtained at a B Factory operating at the $\Upsilon(5s)$ resonance or at LEP or at hadron machines. This measurement is complicated by the rapid oscillations in the time-dependent asymmetry due to the expected large mixing rate in the B_s system. Large data samples and extremely precise vertex measurements will be necessary, though very difficult to obtain, for a significant measurement of γ.

In addition to the study of CP violation in B meson decays, an asymmetric B Factory will permit the search for and measurement of rare B decays, high statistics studies of charm mesons and $\tau^{\pm}$ leptons, Υ spectroscopy and two-photon physics. The operation of a high luminosity, asymmetric e^+e^-storage ring will present major challenges, in particular for B physics where measurements will remain statistics limited. The requirements on design and operation of the detector will be similarly challenging, but most of its components are state of the art, or not far beyond.

There will be substantial competition in the field of B physics from experiments at LEP and also at the Tevatron, where very high production rates and enormous backgrounds place a formidable challenge to the experimenters. Judging from the history of CP experiments in the neutral kaon system, we can look forward to several generations of experiments that will be designed to solve the CP puzzle.

ACKNOWLEDGEMENTS

Much of the material presented here originated from innumerable contributions to B Factory workshops in Europe and the US, and more recently in Japan, and I should like to thank the many friends and colleagues who have participated and taught me the beauty of CP violation in the B system. I apologize for any misrepresentation of their ideas, results, and future rates. Also, because of limitation of space and time, I have chosen not to mention any of the proposals for B physics at future hadron colliders.

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