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The CESR–CLEO Program

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ABSTRACT

The present CESR/CLEO upgrade program, with possible measures to increase further the CESR luminosity, will keep the CESR collider and the CLEO detector productive in the study of CP violation and rare B decays, well beyond the turn-on date of the asymmetric B Factories. I will discuss some, but not all, of the opportunities for making incisive tests of the standard model and revealing the physics beyond the standard model.

1 Status of B Physics

The Cornell Electron Storage Ring is a symmetric energy e^+e^- collider, operating since 1979 at center-of-mass energies near the threshold for b quark production. The Υ(4S) resonance has been the ideal energy for studying the properties and interactions of the B_d and B_u mesons. CESR boasts the world's highest colliding beam luminosity, up to $\mathcal{L}_{pk} = 3.2 \times 10^{32}/\mathrm{cm}^2\mathrm{s}$ and $\int \mathcal{L}dt = 18\ \mathrm{pb}^{-1}$/day. In one day CESR can produce 6000 B^+B^-, 6000 $B^0\overline{B^0}$, 18000 $c\bar{c}$, and 14000 $\tau^+\tau^-$ events.

For the past 16 years CESR and the CLEO collaboration have been leaders in heavy quark and lepton physics. The Υ(4S), Υ(5S), Υ(6S), χ_b(1P), χ_b(2P), B, B^*, and D_s mesons were discovered at CESR, as were the transitions $b \to c$, $b \to u$, and $b \to s$.

In the standard electroweak model the transitions between quark species are accomplished by the emission or absorption of the charged intermediate vector boson $W^{\pm}$. Each of the charge $\frac{2}{3}$ quarks couples to each of the charge $-\frac{1}{3}$ quarks with a vertex factor gV_{ij}, where the V_{ij} elements form the unitary 3×3 Kobayashi-Maskawa matrix [1]. For each matrix element Table 1 shows the expression in terms of the four Wolfenstein parameters [2], our present experimental knowledge of the absolute value (assuming the validity of the standard model but not requiring unitarity), and an example of the kind of process used for the measurement.

Our rather imperfect information of the ρ and η parameters is best specified in terms of the location of the apex of the triangle (Fig. 1) in the complex plane implied by the unitarity relation,

$$V_{td}V_{tb}^* + V_{cd}V_{cb}^* + V_{ud}V_{ub}^* = 0. \tag{1}$$

The magnitude of CP violating effects should be proportional to the area of the triangle.

It was the CLEO discovery of the $b \to u$ transition [3] that established that all of the KM matrix elements are nonzero (assuming unitarity), thus allowing CP violation in B decay.

Table 1: Kobayashi-Maskawa Matrix Elements (model uncertainties in italics)

$V_{ud} = 1 - \lambda^2/2$	0.974 ± 0.0010	$n \to pe\overline{\nu}$	nuclear β decay
$V_{us} = \lambda$	0.2205 ± 0.0018	$K \to \pi\pi$	strange decay
$V_{cd} = -\lambda$	1.01 ± 0.18	$D \to K\pi$	charm decay
$V_{cs} = 1 - \lambda^2/2$	0.204 ± 0.017	$D \to \pi\pi$	no-s charm decay
$V_{cb} = A\lambda^2$	$0.040 \pm 0.002 \pm \mathit{0.002}$	$B \to De\nu$	b decay
$V_{ub} = A\lambda^3(\rho - i\eta)$	$0.0034 \pm 0.0002 \pm \mathit{0.0008}$	$B \to \pi e\nu$	charmless b decay
$V_{ts} = -A\lambda^2$	$0.037 \pm 0.006 \pm \mathit{0.008}$	$B \to K^*\gamma$	penguin decay
$V_{td} = A\lambda^3(1 - \rho - i\eta)$	$0.010 \pm 0.0004 \pm \mathit{0.003}$	$B^0 \leftrightarrow \overline{B^0}$	mixing

This determination of $|V_{ub}|$ and the measurements of $|V_{cb}|$ [4] and $B^0\overline{B^0}$ mixing [5] give us the three sides of the unitarity triangle, and challenge us to measure the three angles through the observation of CP asymmetries in the decays of neutral B's [6]. Agreement between the sides and angles should tell us whether the KM mechanism for CP violation is valid.

This exciting physics opportunity, plus the idea of boosting the $B\overline{B}$ frame by colliding e^+ and e^- with different energies [7], brought new players into the field. Now that work has begun on upgrading PEP [8] and building KEK-B [9] as asymmetric B Factories, it is fair to ask, *what is the future for CESR?*

2 CP Violation

2.1 Time dependent CP violation

To observe a CP violation in B meson decays we look for a $B\overline{B}$ asymmetry arising from the interference of two amplitudes that have different weak phases. The $B^0 - \overline{B^0}$ mixing amplitude can provide the alternate decay route needed for interference. That is, a non-flavor-specific final state f^0 like ψK_S can be reached by either B^0 directly or after oscillating to $\overline{B^0}$. The corresponding decay to $\overline{f^0}$ starting from a produced $\overline{B^0}$ can have a different rate. To know whether the produced meson was a B^0 or a $\overline{B^0}$ we rely on the fact that B mesons are produced in pairs of opposite flavor and tag the flavor of one B by observing the other decaying into a flavor-specific final state: $b \to \ell^- X$ versus $\overline{b} \to \ell^+ X$ or $b \to c \to s$ versus $\overline{b} \to \overline{c} \to \overline{s}$.

Since two neutral B's produced in an e^+e^- collision will oscillate to their antiparticles in a correlated way, we have to consider the joint time evolution of the $B_f B_{tag}$ pair [6], which has the form

$$\frac{d^2N}{dt_f dt_{tag}} = \frac{N}{2\tau^2} e^{-t_f/\tau} e^{-t_{tag}/\tau} \left(1 - q \sin 2\phi \cdot \sin x_d \frac{t_f - t_{tag}}{\tau}\right) \qquad (2)$$

if there are no other interference effects. N is the total number of measured tagged events,

Figure 1: The unitarity triangle drawn in $\rho - \eta$ space. The lengths of the sides correspond to the terms in the unitarity relation, divided by $|V_{cd}V_{cb}^*|^2 = A\lambda^3$. The shaded area shows the allowed region for the location of the upper vertex implied by the measurements of $|V_{ub}|$ (arcs centered on 0,0) and $B^0\overline{B^0}$ mixing (arcs centered on 1,0).

τ is the B^0 mean lifetime, $x_d = \Delta m \tau \approx 0.7$ is the mixing rate, and $q = \pm 1$ is the sign of the charge of the tag.

The second term in the brackets contains the CP violating phase difference $\phi = \frac{1}{2}\phi_{M12} - \phi_f$, where ϕ_{M12} is the phase of the $(B^0\ \overline{B^0})$ mass matrix element M_{12} responsible for $B^0\overline{B^0}$ mixing, and ϕ_f depends on the quark transitions in the $B^0 \to f^0$ and $\overline{B^0} \to f^0$ decays. In the standard model M_{12} is proportional to $(V_{tb}V_{td}^*)^2$. From mixing data we know $|M_{12}|$, but ϕ_{M12} is not known experimentally. The standard model predicts $\phi_f = \arg(V_{cb}V_{cd}^*)$ for decay modes involving charm, such as ψK_S, and $\phi_f = \arg(V_{ub}V_{ud}^*)$ for charmless modes, like $\pi^+\pi^-$. Thus the phase ϕ appearing in equation (2) corresponds to one of the angles in the unitarity triangle (Fig. 1) — angle β for modes involving charm (e.g., ψK_S) and angle α for charmless modes (e.g., $\pi^+\pi^-$). If one can measure the CP violating asymmetry in one or several modes in each category, one will then have direct measurements of two of the angles in the unitarity triangle. The third angle γ cannot be measured directly in neutral B decays.

The favored e^+e^- center-of-mass energy for the measurement is at the $\Upsilon(4S)$ resonance, because of the large cross section and the clean $B\overline{B}$ final state. However, since the CP violating term in equation (2) is odd in $t_f - t_{tag}$, the corresponding overall rate asymmetry for $q = +1$ versus $q = -1$ vanishes identically. To see a CP violation one has to be sensitive to the asymmetry in the time dependent differential decay rates. The favored technique [7] is to boost the $B\overline{B}$ system by colliding e^+ and e^- of different energies in order to make the decay lengths of the B of interest and the B that tags the initial flavor more easily measurable.

Figure 2: Survey of models and their effect on the unitarity triangle, from Nir and Quinn.

2.2 Time independent CP violation

On the other hand, this is not the only measurement that will be required to understand CP violation. Many theorists working on the problem of cosmic baryogenesis insist that the standard KM matrix mechanism for CP violation cannot explain the baryon asymmetry in the present universe [10]. Nonstandard models typically involve hypothetical particles – charged Higgs, fourth generation quarks and leptons, supersymmetric partners (squarks, gluinos, charginos, higgsinos), right-handed W's and Z's [11, 12, 13]. Of the eight nonstandard models surveyed by Nir and Quinn [12] (see Fig. 2) four of them — four generations, Z-mediated FCNC, supersymmetry, and superweak – can mimic the standard model if you know only the α and β angles. Figure 3, for instance, shows the area of the $\rho - \eta$ plane for which measurements of $\sin 2\alpha$ and $\sin 2\beta$ to 10% and 5% respectively are consistent with either the standard model or the superweak model [13].

It will therefore be necessary to measure all three angles, α, β, and γ. The first two can in principle be measured in mixing mediated $B^0\overline{B^0}$ decays as just described, but γ cannot be determined in this way at the Υ(4S). Measurements are possible in B_s decays, running at the Υ(5S) resonance, but the luminosities required are more than an order of magnitude higher, making that a very unlikely prospect. In order to measure γ in $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\overline{B}$ we will need to observe a B versus $\overline{B}$ decay rate asymmetry that comes from the interference of two direct decay amplitudes leading to the same final state.

Although the identification of the initial flavor, B or $\overline{B}$, is easiest in the case of charged B's, it is possible to measure a B versus $\overline{B}$ asymmetry also in the case of neutral B's, either

Figure 3: The region in $\rho - \eta$ space that is consistent with either the Kobayashi-Maskawa CP violation mechanism or the superweak model, when $\sin 2\alpha$ is measured to $\pm 10\%$ and $\sin 2\beta$ is measured to $\pm 5\%$.

when some quantum number in the final state, like strangeness, can discriminate between B and $\overline{B}$, or when the flavor of the decaying B or $\overline{B}$ is tagged by observing its partner antiparticle. Even in the case of decay to a CP eigenstate, like $\pi^+\pi^-$ or $\pi^0\pi^0$, whenever there are two interfering direct decay amplitudes, there can be an extra term in the $dN/dt_f dt_{tag}$ joint distribution (equation 2) that is proportional to $q \cos x_d \frac{t_f - t_{tag}}{\tau}$ and does not integrate to zero in the total rate.

2.3 Example: $B^\pm \to K^\pm \pi^0$

For illustration let us consider the the rates for the two CP-conjugate processes $B^+ \to K^+\pi^0$ and $B^- \to K^-\pi^0$. Each decay has contributions from tree and loop amplitudes. The tree amplitude A_1 (see Fig. 4a) for $B^- \to K^-\pi^0$ involves $V_{ub}V_{us}^*$ and can therefore be written in the Wolfenstein representation as

$$A_1 = a_1 A \lambda^4 \sqrt{\rho^2 + \eta^2} e^{-i\gamma}. \tag{3}$$

The CP-conjugate tree amplitude $\overline{A_1}$ for $B^+ \to K^+\pi^0$ is the same, but with the complex conjugate weak phase factor $e^{+i\gamma}$. The weak phase $\gamma = \tan^{-1}(\eta/\rho)$ is actually the lower-left angle in the unitarity triangle (Fig. 1), which is not accessible to mixing mediated CP violation measurements on neutral B decays. The available data on the lengths of the sides of the triangle imply $\gamma = 1.5 \pm 0.3$ radians [14]. For this diagram the strong interaction contribution to the phase can be taken to be zero.

The amplitude A_2 involves a quark+W loop, the penguin process (see Fig. 4b). Of the three possibilities for the quark in the loop, the u is suppressed by an extra factor of

Figure 4: B decay amplitudes: (a) tree diagram for $B^- \to K^-\pi^0$ and (b) loop (penguin) diagram for $B^- \to K^-\pi^0$; (c) external tree diagram for $B^- \to D^0 K^-$ and (d) internal tree diagram for $B^- \to \overline{D^0} K^-$.

$\lambda^2 = 0.05$, leaving the c and t dominant [15, 16]. The fact that $c\overline{c} \to u\overline{u}$ can proceed with $c\overline{c}$ on the mass shell enhances the diagram with c in the loop. Although the amplitude involves $V_{cb}V_{cs}^*$ and $V_{tb}V_{ts}^*$, the unitarity of the KM matrix and the smallness of $V_{ub}V_{us}^*$ imply that $A_{2,c} \propto V_{cb}V_{cs}^*$ and $A_{2,t} \propto V_{tb}V_{ts}^*$ have essentially the same weak phase, and the sum can be represented as

$$A_2 = a_2 A \lambda^2. \tag{4}$$

In the Wolfenstein representation there is no weak interaction contribution to the phase, and the $\overline{A_2}$ loop amplitude for the CP conjugate decay, $B^+ \to K^+\pi^0$ is the same. The $c\overline{c} \to u\overline{u}$ process has an absorptive part, which provides a nonzero strong interaction phase δ. Depending on the q^2 given to the gluon, and ignoring final state absorptive effects that vary with the exclusive hadronic channel, the phase is expected to be in the range $0 < \delta < 13°$ [16]. More sophisticated calculations give results as high as $\delta = 30°$ [17].

The decay rate asymmetry is

$$\mathcal{A} = \frac{|A_1 + A_2|^2 - |\overline{A_1} + \overline{A_2}|^2}{|A_1 + A_2|^2 + |\overline{A_1} + \overline{A_2}|^2} = \frac{-2\sin\delta\sin\gamma}{R_{12} + 1/R_{12} + 2\cos\delta\cos\gamma}, \tag{5}$$

where

$$R_{12} = \frac{|A_1|}{|A_2|} = \frac{a_1}{a_2}\lambda^2\sqrt{\rho^2 + \eta^2}. \tag{6}$$

The ratio R_{12} of tree and loop amplitudes is expected to be around 0.2 [18, 17], implying $\mathcal{A} \sim -0.4\sin\delta\sin\gamma$. Thus if the standard model is correct, the $B^\pm \to K^\pm\pi^0$ asymmetry could be anywhere from 1% to 18%, depending on the value of the strong phase δ. The effect might be observable with a 50 fb^{-1} data sample, or it might require more than 500 fb^{-1}. Note that in the superweak model referred to above, the asymmetry would be zero, and the measured α, β, and γ would not be consistent with the standard model unitarity triangle.

The loop amplitude A_2 is particularly vulnerable to contributions from higher mass particles, like fourth generation quarks, leptoquarks, squarks, gluinos, charged Higgs, charginos,

Table 2: Standard model predictions of branching ratios and CP asymmetries [17]

Mode	$\mathcal{B}$, 10^{-6}	$\mathcal{A}$, %	$1/\mathcal{B}\mathcal{A}^2$, 10^6
$K^-\pi^0$	8	18	4
$K^-\pi^+$	13	22	1.7
$K^-\eta$	0.09	-65	26
$K^-\eta'$	9	-1.2	800
$\pi^-\overline{K^0}$	8	-0.9	1500
$\pi^-\pi^0$	1.3	-70	1.5
$\pi^-\eta$	5	33	1.9
$\pi^-\eta'$	6	16	7

and right-handed W's. The asymmetry can be much more impressive in non-standard models. In any model with charged Higgs bosons [19] there is an additional diagram in which the Higgs substitutes for the W in the penguin loop. If a Higgs loop and the standard W loop both contributed and involved the same quarks, the two weak phases would be the same, and the combined loop amplitude A_2 would still follow equation (4), but with the magnitude a_2 and phase δ different from the standard model expectation.

In the past, theorists have not favored this kind of experiment because the size of the CP asymmetry depends not only on $\sin\gamma$ but also on nonperturbative hadronic parameters, a_1/a_2 and δ. However, since the asymmetric B Factories were first proposed, analyses have shown that a measurement of the decay rates for closely related modes provides the information needed to extract γ from the $K^\pm\pi^0$ asymmetry measurement [21]. That is, measurements of branching ratios for $K^\pm\pi^0$, $\pi^\pm K^0$, $K^\pm\eta$, $K^\pm\eta'$, and $\pi^\pm\pi^0$ allow one to solve for the separate contributions of external and internal tree diagrams to A_1 and gluonic and electroweak penguin diagrams to A_2, and thus to determine a_1, a_2, and δ experimentally. By the time that data samples are sufficient to allow a measurement of the CP violating asymmetry $K^\pm\pi^0$, the related branching ratios will already be known. The same arguments apply for decay modes of the form $B \to K^* + (\rho \text{ or } \omega)$.

2.4 Other examples

There are dozens of two-body decay modes that proceed through tree+loop amplitudes. There might be one with a lucky combination of a_1, a_2, and δ leading to a large sensitivity to $\sin\gamma$. For example, if $R_{12} \approx 1$ and $\delta \approx 90^\circ$, the CP violating asymmetry is $\mathcal{A} \approx -\sin\gamma$, greatly enhanced over the standard model prediction for $B^\pm \to K^\pm\pi^0$. Table 2 shows recent standard model calculations [17] of the branching ratios and asymmetries for some two-body tree+loop modes. The calculation takes into account electroweak and gluonic penguins with timelike and spacelike hard gluons, and assumes $\sin\gamma = 0.943$. The table also gives the $1/\mathcal{B}\mathcal{A}^2$ factor that determines the size of the $B\overline{B}$ event sample required to show a CP

asymmetry significant to s standard deviations:

$$N_{B\overline{B}} = \frac{s^2}{\mathcal{B}\mathcal{A}^2\epsilon},$$

where ϵ is the detection efficiency. Note that it may be possible to see a three-standard-deviation CP violation $B^\pm \to \pi^\pm\pi^0$ with less than 20 fb^{-1} of integrated luminosity.

More generally, for any B decay mode with two interfering amplitudes involving different KM matrix elements, the rate asymmetry will have the form of equation (5) with the strong phase difference replacing δ and the weak phase difference replacing $-\gamma$. An example [22] is the asymmetry in the rates for the decays $B^\pm \to D_{CP}K^\pm$, where D_{CP} denotes a D^0 or $\overline{D^0}$ that decays to a CP eigenstate, like K^+K^- or $\pi^+\pi^-$. This decay involves interference between the external spectator amplitude (Fig. 4c)

$$A_1(b\overline{u} \to c\overline{u} + s\overline{u}) \propto V_{cb}V_{us}^* = A\lambda^3$$

and the color suppressed internal spectator amplitude (Fig. 4d)

$$A_2(b\overline{u} \to u\overline{c} + s\overline{u}) \propto V_{ub}V_{cs}^* = A\lambda^3(1-\lambda^2/2)\sqrt{\rho^2+\eta^2}e^{-i\gamma}.$$

The expected magnitude of the CP violating asymmetry $\mathcal{A}$ is helped by the likelihood that the two interfering amplitudes are similar ($R_{12} \approx 1$ in equation 5), but the strong phase difference δ may be rather small. Also, the branching ratios for D^0 decays to CP eigenstates are small. The asymmetry is proportional to $\sin\gamma$.

CLEO has been looking for $B^\pm \to \pi^\pm\pi^+\pi^-$ and other non-resonant three-body modes. Deshpande et al. [23], suggest a CP violating asymmetry $\mathcal{A} = (0.40 - 0.48)\sin\gamma$ from interference between the $\pi\pi\pi$ mode and $B^- \to \chi_{c0}\pi^-, \chi_{c0} \to \pi^+\pi^-$. They predict $\mathcal{B}(\pi^-\pi^+\pi^-) = (1.5 - 8.4) \times 10^{-5}$. CLEO sees a few events in the signal region, consistent with expected backgrounds, although more work is required to understand the backgrounds. The upper limit branching fraction is around 4×10^{-5}, which starts to rule out the upper range of the theoretical prediction.

A recent analysis of $b \to s\gamma$ versus $\overline{b} \to \overline{s}\gamma$ [20] suggests that the asymmetry could be as large as 10% in the two-Higgs-doublet model.

If the standard Kobayashi-Maskawa mechanism for CP violation is correct, one can get better accuracy on $\sin\gamma$ by measuring rate asymmetries in several pairs of CP-conjugate decay modes, but if nature is nonstandard, different modes may not give the same apparent $\sin\gamma$ result, and one can learn some new physics from the differences.

3 Rare B decays

Although the B Factory proposals were prompted by the goal of understanding CP violation, that may turn out not to be the most exciting B physics in the next decade. If the CP measurements of the angles in the unitarity triangle confirm what we will already know from the sides, they could turn out to be rather boring. It is unlikely that the angle determinations from CP asymmetries will ever rival in accuracy the angles implied by the measurements of the sides, once we have reliable lattice calculations of f_B and other QCD effects. On the other hand, rare B decays may tell us about physics beyond the standard model.

Since its partner t quark is heavier, the b quark can decay directly only through off-diagonal KM matrix elements, V_{cb} and V_{ub}. The situation is similar to the decay of the strange quark, but in the case of the b quark the suppression of the favored decays is greater ($V_{cb} = 0.04$ versus $V_{us} = 0.22$). The resulting rate suppression allows rare processes to compete. The search for unusual decays of B mesons is therefore a sensitive probe for new physics beyond the standard model.

A B decay mode is termed rare if it does not proceed through the dominant $b \to c$ coupling. The other possibilities in the standard model are the $b \to u$ coupling, suppressed in rate by the KM factor $|V_{ub}/V_{cb}|^2 = \lambda^2(\rho^2 + \eta^2) \approx 0.01$, and the effective flavor-changing neutral current transitions $b \to s$ and $b \to d$.

3.1 Electromagnetic penguin decays

The first $b \to s$ loop decays were seen in the exclusive $B \to K^*\gamma$ mode. The measured branching ratio for $B^0 \to K^{*0}\gamma$ is $(4.3^{+1.1}_{-1.0} \pm 0.6) \times 10^{-5}$ [24]. CLEO now sees signals in all four K^* decay channels, $K^+\pi^-$, $K^0_S\pi^0$, $K^+\pi^0$, and $K^0_S\pi^+$. Although theoretical estimates of the fraction of $b \to s\gamma$ that should materialize as $K^*(890)$ cover the range from 2% to 40%, the rate for the quark level $b \to s\gamma$ process *is* reliably calculated in the standard model. Inclusive $B \to X_s\gamma$ is therefore the important rate to measure. The recent CLEO data [25] give $\mathcal{B}(b \to s\gamma) = (2.3 \pm 0.6 \pm 0.4) \times 10^{-4}$, consistent with the standard model prediction. The heaviest particles in the loop, say $t + W$, dominate the amplitude. In nonstandard models the rates for loop decays are extraordinarily sensitive to new physics at high mass scales. In the simplest form of the minimal supersymmetric model the CLEO $b \to s\gamma$ data restrict the charged Higgs mass to be greater than 260 GeV — a rather remarkable conclusion from a few dozen events at a 10 GeV center-of-mass energy. More generally, though, there is enough latitude in SUSY models to match almost any experimental result. For instance, a loop diagram in which a chargino and squark substitute for the W and heavy quark could cancel the effect of the charged Higgs amplitude on the branching ratio [26]. The $\mathcal{B}(b \to s\gamma)$ result also puts stringent limits on anomalous $WW\gamma$ and $tt\gamma$ couplings.

CLEO has also searched for the $b \to d$ process in the $B^0 \to \rho^0\gamma$ channel. In the signal region we expect 0.6 ± 0.2 $\rho^0\gamma$ events and 1.1 ± 0.2 background events. The four candidates that we see in the signal region are probably an unlikely feed-through from $K^*\gamma$. In the standard model this decay is probably our best chance for a reliable measurement of V_{td} from the relation

$$|V_{td}|^2 = \frac{\mathcal{B}(\rho\gamma)}{\mathcal{B}(K^*\gamma)}|V_{cb}|^2.$$

More generally, it is an additional opportunity to see contributions from higher mass particles in extensions of the standard model.

CLEO continues to search for dilepton modes involving $b \to s\ell^+\ell^-$. The dilepton can arise in the standard model from a virtual photon, Z^0, or vector meson, or can be produced from a box diagram. The expected inclusive branching ratio is 10^{-5} [38], although nonstandard physics could enhance the rates [39]. The present upper limits are around 10^{-5} for each of the four exclusive channels (K^+ or K^{*0})(e^+e^- or $\mu^+\mu^-$) [40]. CLEO is also investigating $b \to s\nu\bar{\nu}$, which is predicted to occur at the level of 5×10^{-5} [15] in the standard model. In other models a new gauge boson X^0, mixing with Z^0 and coupling mainly to the third generation, can be used to explain $\mathcal{B}(Z \to b\bar{b})$, the top mass, and the B semi-leptonic branching fraction. These models also cause anomalous $b \to s\nu_\tau\bar{\nu}_\tau$ branching fractions, perhaps as high as 10% [41].

The $B \to \gamma\gamma$ decay is an electromagnetic penguin annihilation decay involving V_{td} and an extra photon. The standard model prediction for the branching fraction is therefore very low, 6×10^{-10}, leaving plenty of opportunity for nonstandard effects to dominate. CLEO sees no events in the signal region, and derives an upper limit on the branching fraction of 3×10^{-6}.

3.2 Gluonic penguin decays

In contrast to the electromagnetic $b \to s\gamma$ transitions, the purely hadronic $b \to sg$ decays are less reliably predicted in the standard model. They are especially interesting, though, because of the possibility of measurable CP violating effects. The expected $b \to sg$ branching ratio is about 10^{-3}. As in the case of $b \to s\gamma$, higher mass objects such as charged Higgs could substitute in the loop for the heavy quark or W. Technicolor or supersymmetry models could even enhance $b \to sg$ while at the same time not enhancing $b \to s\gamma$, thus accounting for the puzzling B semi-leptonic branching fraction and low inclusive charm yield.

$B \to \phi X_s$ is the probably clearest example of a decay dominated by the $b \to sg$ amplitude. Other likely examples are $B \to K_S X$ and $B \to \eta' X$. CLEO is looking for these modes by looking for inclusive ϕ, K_S, and η' beyond the kinematic endpoint for $b \to c$ decays, that is, typically 2.0 to 2.7 GeV/c [27]. One possible problem is that η''s from $B \to D^{(*)0}\eta'$ leak into the signal region. To distinguish the η' sources, one can also look for $B \to \eta X$. Since the $b \to sg$ signal couples to the $s\bar{s}$ component, there should be four times as many η as η'. On the other hand, if $D\eta$ is the source of η's, the signal couples to the $d\bar{d}$ component, which gives the same number of η and η'. Preliminary studies show nice η' mass peaks in CLEO on-resonance data, which are completely consistent with coming entirely from the u, d, s, c continuum. Expected sensitivity for $\mathcal{B}(B \to \eta' X_s)$ is a few 10^{-4}. The K_S momentum spectrum shows no excess in the $b \to sg$ signal region. Again, the expected sensitivity is a few 10^{-4}.

Figure 5 shows the present CLEO branching ratio upper limits for many rare B decay modes [28], including some that have contributions from gluonic penguins amplitudes. It also shows the range of standard model predictions. The present limits, based on about 3 fb^{-1} of luminosity at the $\Upsilon(4S)$, are approaching the interesting levels. The most suggestive signals are in $K^+\pi^-$ and $K^+\pi^0$, which are unfortunately difficult to distinguish from the also

Figure 5: Branching ratios for various rare two-body exclusive B decay modes. CLEO upper limits are indicated by $\times$; the range of standard model predictions is shown by — .

rare $\pi^+\pi^-$ and $\pi^+\pi^0$ [29, 28]. The systematic study of these decays, just now beginning, could be an important window on new physics as data samples increase. One or two orders of magnitude more in integrated luminosity are needed to bring the experimental limits or measured values into the range of the standard model predictions. Table 2 shows predictions for some of the modes that are most favorable for the observation of CP violating asymmetries.

3.3 b to u decays

The KM matrix element V_{ub} is a fundamental parameter of the standard model. It determines the length of one side of the unitarity triangle, whose area determines the degree of CP violation in B meson decay. Our present information comes from the observation of semileptonic B decays with lepton momenta beyond the end point for $B \to D\ell\nu$ [3]. The accuracy is limited by the model dependence in extrapolating the measured lepton spectrum to lower momenta. Nonleptonic $b \to u$ decays are of special interest, because (a) they offer an independent check of V_{ub} with different model dependences, and (b) CP violating asymmetries are expected to be measurably large in exclusive hadronic $b \to u$ decay modes, such as $B \to \pi\pi$ (Table 2). These decays can also have penguin $b \to d$ contributions in addition to the tree $b \to u$ amplitude. Such "penguin pollution" effects could falsify the conclusions from the measurements of time dependent CP asymmetries for modes like $\pi^+\pi^-$ if they are not understood and taken into account. To unravel the separate contributing amplitudes one needs to measure rates for different charge combinations — $\pi^+\pi^-$, $\pi^\pm\pi^0$, and $\pi^0\pi^0$.

An indication for one such decay, $B \to \pi^+\pi^-$, has already been reported by CLEO [29].

The present CLEO detector can distinguish individual $B \to \pi^+\pi^-$ events from $B \to K^+\pi^-$ only at the 2.5 standard deviation level, by combining dE/dx (1.8 s.d. $K - \pi$ separation) and kinematics (1.7 s.d. shift in reconstructed m_B). So the sum of the two branching ratios,

$$\mathcal{B}(B \to \pi^-\pi^+) + \mathcal{B}(B \to K^-\pi^+) = (2.4 \pm 0.8) \times 10^{-5},$$

is better measured than either the $\pi^-\pi^+$ or $K^-\pi^+$ branching ratio. Table 2 shows some recent predictions. The number of events will increase with the upgraded CESR luminosity and the reliability of the signal will improve with the new CLEO particle identification.

Figure 5 shows the CLEO limits and standard model predictions for the exclusive two-body $b \to u$ decays involving nonstrange light mesons, like $\pi^-\pi^+$. As data samples get larger these modes will come into range and will serve as alternative measures of V_{ub}. A study of the pattern of branching ratios in the various modes will be necessary for the detailed understanding of the mechanisms responsible for these decays, which in turn will be essential for the interpretation of CP violating asymmetries.

3.4 Other rare B topics

Decays to baryon-antibaryon pairs. The B can decay to baryons. It therefore offers a unique opportunity to study the dynamics of baryon pair creation in a reaction where at least the initial state and the initial coupling are well defined. Even at the most fundamental level we are completely ignorant of the production mechanism. For example, does it proceed through diquark-antidiquark pairs? There are data from CLEO and ARGUS on inclusive proton, Λ, Λ_c, Σ_c, and Ξ_c yields in B decay [30], and CLEO has recently put a limit on the contribution of the internal spectator $b \to c + \bar{c}s$ process to B-to-charmed-baryon decays. Because of the low efficiencies for reconstructing exclusive decays of B mesons and charmed baryons, a definitive study must await larger data samples.

Purely leptonic decays. In the standard model the purely leptonic decay of the B into lepton and neutrino should proceed as in pion decay, through the annihilation of the b and $\bar{u}$ quarks into a W^-, materializing as $\ell^- + \bar{\nu}$. The rate is proportional to $|V_{ub}|^2$ and to the $b\bar{u}$ bound-state overlap factor f_B^2. Once V_{ub} is known, a measurement can give us an experimental value for f_B, which comes into calculations of mixing, CP violation, and other weak processes involving the interaction between the quarks in the B meson. Theoretical predictions for f_B from QCD sum rules [31] and lattice calculations [33] cover the range from 105 to 187 MeV. The present branching ratio upper limits, from CLEO [32], are

$$\begin{aligned} B^- \to \quad & e^-\bar{\nu}_e & < 1.5 \times 10^{-5}, \\ & \mu^-\bar{\nu}_\mu & < 2.1 \times 10^{-5}, \\ & \tau^-\bar{\nu}_\tau & < 2.2 \times 10^{3}. \end{aligned}$$

The leptonic decay rate is also sensitive to new physics; for example, the mass $m_{t\pi}$ and coupling λ of a possible technipion can be limited [34] by

$$\frac{m_{t\pi}}{\lambda} = 200\mathrm{GeV} \left(\frac{10^{-6}}{\mathcal{B}(B \to \tau\bar{\nu})} \right)^{1/4}.$$

Since the rate should be proportional to the square of the lepton mass, the most copious mode is $B \to \tau\overline{\nu}$, which however is identifiable only in tagged $B\overline{B}$ events, because of the missing neutrinos (see the next section). The much smaller branching ratio for $B \to \mu\overline{\nu}$, about 10^{-7}, might be measurable without tagging, since the muons will be nearly monoenergetic near the $B\overline{B}$ threshold. Very high luminosities may be required, however, since a B branching ratio of 10^{-7} yields only about one event per 10 fb^{-1} at the $\Upsilon(4S)$. Non-standard model enhancements, however, could give a much larger event rate.

Dilepton decays. Certain B decays are strictly forbidden in the standard model, for example, those that violate an accepted conservation law. Still other decays may be allowed but at an undetectably low branching ratio. In the cases in which the particular final state is easily recognizable experimentally and not obscured by backgrounds, the search for such modes can expose weaknesses in the model. Typical examples are $B \to \mu e$ and $B \to \tau\mu$, which are forbidden by the absence of transitions between lepton families in the standard model. If there were a "horizontal gauge boson" H^0 that would allow $b\overline{d} \to H^0 \to \mu e$, the branching ratio for $B \to \mu e$ would be [35]

$$130\left(\frac{m_W}{M_H}\right)^4\left(\frac{f_B}{100\ \text{MeV}}\right)^2 .$$

$B \to \ell^+\ell^-$ decays can occur in the standard model via box diagrams or penguin annihilation diagrams, but are suppressed to the level $10^{-10} - 10^{-15}$. If there are flavor-changing neutral currents however, these decays can occur via tree-level diagrams, so this is a good place to look for new physics [36]. Since backgrounds are negligible, the CLEO searches for the modes e^+e^-, $\mu^+\mu^-$ and $e^\pm\mu^\mp$ are limited only by the size of the available event sample. The 1994 data [37] implied a lower limit on the mass of the horizontal gauge boson of 8 TeV. The mass sensitivity increases as the fourth root of the number of B decays searched.

3.5 Fully tagged B's.

There is another category of B physics that requires very large data samples, although it does not fit our narrow definition of 'rare'. That is the systematic study of fully tagged B decays. The set of $\Upsilon(4S)$ events in which one B has been kinematically reconstructed provides an unbiased sample of tagged B decays of known charge state and vector momentum, and we know which tracks belong to each B. The set of tagged B's contains all decay modes and configurations in the same proportion as in the complete sample, unbiased by any detection requirements. In the past the tagged measurements have been limited by the small number of reconstructed B decays. Depending on the desired purity of the tagged sample, it is typically less than 10^{-3} of the full $B\overline{B}$ data set. For a 'copious' 1% decay the effective tagged branching ratio becomes 10^{-5}, thereby putting it in the 'rare' category. With much higher luminosities there are a number of physics topics that can be profitably pursued. Here are several examples.

Semileptonic $b \to c$ decays. One can make 1-c reconstructions of decays with a single missing particle, for instance, semileptonic B decays. In the tagged B sample one can isolate the exclusive semileptonic decay channels $B \to D^{(*)} e^- \overline{\nu}_e$ cleanly over the entire range of q^2. This will allow us to extend the range of measurements of the momentum transfer and helicity structure. Reliable measurements of the various B to $D^{(*)}$ form factors will provide important tests of heavy quark effective theory and QCD effects, as well as an accurate, model independent measurement of V_{cb}.

Semileptonic $b \to u$ decays. The $b \to u$ decay process for which the rate is most reliably related to the important Kobayashi-Maskawa matrix element V_{ub} is the charmless semileptonic decay, $b \to u\ell\overline{\nu}$. The present measurement error is dominated by the model dependence in extracting the total rate from the data near the lepton momentum endpoint. A tagged event sample would enable one to use the whole spectrum and avoid the model dependent extrapolation.

$B \to \tau\overline{\nu}$ decays. As mentioned above in the section on rare decays, the measurement of the branching ratio for the $B \to \tau\overline{\nu}_\tau$ decay offers a determination of the important f_B parameter. The branching ratio, about 5×10^{-5}, would be accessible in the presently available data sample, but the τ cannot be identified cleanly in generic $B\overline{B}$ events, because of the missing neutrinos, both in the B decay and in the τ decay. However, if one of the B's is reconstructed, it tags all the other secondaries in the event as belonging to the partner B, and the τ signal can be isolated. The measurement puts a heavy premium on luminosity, requiring over 10^6 tagged B events, an integrated luminosity of about 100 fb^{-1}. The box-diagram $B \to \nu\overline{\nu}$ decay also becomes accessible in a large tagged data sample.

4 The CESR Luminosity Upgrade Program

There are two major differences between an asymmetric B Factory and the present CESR — the energy asymmetry and the luminosity. Let us discuss the luminosity first. Based on the requirements for the measurement of the α and β angles in the unitarity triangle, PEP2 proposes to run at 30 fb^{-1} per year [8]. CESR running at the present best luminosity of 18 pb^{-1} per day for 200 days in a year is capable of 3.6 fb^{-1} per year, a luminosity level about an order of magnitude less than that of a successful B Factory.

4.1 Phase II

CESR, however, will do better. The April '95 peak luminosity record of $3.2 \times 10^{32}/\mathrm{cm}^2\mathrm{s}$ was achieved by electrostatically separating the electron and positron orbits in a pretzel configuration and intersecting them at a ± 2 mrad crossing angle at the center of the CLEO detector (Fig. 9). There were 18 circulating bunches of 1.4×10^{10} particles per bunch in each beam. At the intersection point the depth of focus parameter was $\beta^* = 1.8$ cm, and the limiting beam-beam tune shift was $\xi = 0.033$. This record luminosity is only marginally better than the 2.9×10^{32} reached with the earlier 7-bunch head-on collisions, because the April '95 interaction region geometry was not compatible with the crossing beam configuration. In order to get the nominal 18/7 factor of luminosity gain, we needed (a) more aperture in the I.R. focusing quads to accommodate the beam crossing angle, and (b) shorter

Figure 6: Layout of the CLEO and CESR components in the interaction region for the present phase II configuration. The diagram shows a vertical section with the interaction point at the left. The CESR solenoid pole is in the center.

focal lengths to move the maximum in the β function closer to the I.P. instead of near the first parasitic bunch crossing at 4.2 m from the I.P. These modifications have now been made during the April–October '95 shutdown (see Fig. 6), and we are ready to try for a new luminosity record. While it may be naive to assume that all the other parameters remain the same when we increase the bunch frequency, within the next year we can optimistically hope for $\mathcal{L}_{pk} = \frac{18}{7} \times 2.9 \times 10^{32} = 7.5 \times 10^{32}$ — more conservatively, let's say 6×10^{32}. Moreover, if we can succeed in increasing from 2 to 3 the number of bunches in each of the nine bunch trains, keeping the interbunch spacing at 8.4 m, we might even (more optimistically) hope for $\frac{27}{7} \times 2.9 \times 10^{32} = 1.1 \times 10^{33}$.

4.2 Phase III

There's more though. If we can (a) reduce the interbunch spacing to 4.2 m and (b) handle the synchrotron radiation from the extra beam current implied by 9×5 bunches, the naive expectation is $\mathcal{L}_{pk} = \frac{45}{7} \times 2.9 \times 10^{32} = 1.8 \times 10^{33}$. Reducing the interbunch spacing involves replacing the I.R. quads with superconducting quads, and handling the synchrotron radiation without destabilizing the beam involves superconducting rf cavities and modifications to the vacuum system. These improvements are part of the 'Phase III' CESR/CLEO capital upgrade approved by the NSF in early 1995 and scheduled for installation in 1997-98 [42]. Figure 7 shows the phase III layout at the interaction region. If all goes well, we can expect CESR to be running with a peak luminosity over 10^{33} by 1999, and logging an integrated luminosity of over 10 fb^{-1} per year — optimistically, one could hope for as much as a factor of 1.8 more.

Table 3 shows estimates of CESR luminosity, based on the 1995 phase II work and the

Table 3: Luminosity projections

year	fb^{-1} /yr.	*CESR* cum.	fb^{-1} /yr.	*PEP2* cum.
1991-95	6	6	0	0
1996	3	9	0	0
97	6	15	0	0
98	1	16	0	0
99	5	20	5	5
2000	12	32	10	15
01	15	47	20	25
02	15	62	30	55
03	15	77	30	85

1997-98 installation of the phase III upgrade. For comparison, the two last columns show the corresponding figures for the SLAC asymmetric B Factory. Although PEP2 is scheduled to begin operating with the BaBar detector in 1999, asymmetric operation of a new double-ring configuration will certainly not reach design luminosity immediately. A learning curve covering about two years may be reasonable, even optimistic. Table 3 shows the PEP2 luminosity profile under this assumption. The luminosity goal for the first stage version of the KEK-B rings is a more modest 1×10^{33}. There is considerable risk in both the CESR and PEP2 luminosity projections, but I believe that the comparison has been made with about the same degree of optimism on the two sides. Both projections are based on detailed upgrade plans already funded and under way.

Table 3 indicates that *if no further measures are taken to increase luminosities* in CESR and PEP2, then the size of the PEP2 data set could overtake the CESR data set by the year 2003, that is, about eight years from now and about five years beyond the end of funding for the present CESR/CLEO capital upgrade program. Of course, if CESR were more successful in reaching its luminosity goals than PEP2, the crossover might never occur. The crossover would be a year or so earlier if CESR were not successful.

4.3 Further possible luminosity improvements

Even if CESR reaches the luminosity goals of the phase III upgrade, there will be a need for more. As we have seen, for CP violating B decay modes, loop decays ($b \to sg$, $b \to s\gamma$, and $b \to s\ell^+\ell^-$), and leptonic decays ($B \to \ell\nu$), as well as for the definitive study of weak form factors with tagged events, the data rates will be low even at 3×10^{33} luminosity. Fortunately, there are ways of going beyond B Factory luminosities in CESR.

The luminosity of a collider (in $cm^{-2}s^{-1}$) in the saturated tune-shift limit is conveniently

Figure 7: Layout of the CLEO and CESR components in the interaction region for the future phase III configuration (cf. Fig. 6).

written as

$$\mathcal{L} = 2.17 \times 10^{34} \frac{(1+r)\xi E e N_b f}{\beta^*},$$

where $r = \sigma_v/\sigma_h$ is the aspect ratio (now < 0.03) at the interaction point, E is the beam energy (5.3) in GeV, eN_bf is the beam current in Amperes (the product of the charge per bunch and the average bunch collision frequency), ξ is the vertical beam-beam tune shift, and β^* is the vertical depth-of-field focusing parameter in cm. It is generally assumed that the number N_b of particles per bunch and the tune-shift ξ have already reached their practical limits. In the past decade the luminosity of CESR has been upgraded by increasing f from 1 bunch per turn to 18, and decreasing β^* from 10 cm to 1.8 cm. The phase III upgrade continues this evolution by increasing f to 45 bunches per turn.

There are two plans under active study now at Cornell for further luminosity gains beyond phase III: (a) colliding round beams ($r = 1$) and increasing the tune-shift limit ξ, and (b) increasing the bunch frequency f to 90 or perhaps even 180 bunches per turn by circulating the e^+ and e^- beams in separate channels.

4.4 Round beams

Krishnagopal and Siemann [43] have argued that if the beam cross section in the transverse plane at the I.P. is made round instead of flat as it is in existing storage rings, then not only does one double the $1 + r$ factor in the luminosity formula, but one also has the possibility of a significantly higher beam-beam tune shift limit ξ. The horizontal emittance generated by synchrotron radiation could be coupled into the vertical plane using skew quadrupoles in a characteristic time of several hundred turns. Another technique has been suggested by Talman at Cornell. In his "Möbius-Twisted Accelerator" [44] a lattice insertion

Figure 8: Conceptual design of a double superconducting quadrupole for CESR. The center-to-center distance is 8 cm.

consisting of upright and skew quadrupole magnets would interchange horizontal and vertical betatron oscillations on each particle passage. The resulting lattice is remarkably insensitive to the beam-beam interaction; the beam-beam tune-shift limit ξ would increase from 0.03 to perhaps as high as 0.15. On the other hand, the practical difficulty of bringing both horizontal and vertical displacements to a good focus at the I.P. dictates a larger vertical β^* (the same for horizontal) for round beams.

There is a plan in spring of 1996 to try round beams in CESR, first with skew quadrupoles, later perhaps with a Möbius insertion in the north straight section opposite the CLEO I.R. We will be able during scheduled machine study shifts to test the round beams in nine-bunch head-on collisions with the existing phase II I.R. quadrupole configuration. The superconducting-plus-permanent-magnet I.R. quadrupole combination being built for the phase III upgrade will also be compatible with the round beam configuration. If we get a sizable tune-shift improvement, we will be encouraged to increase the betatron tune (now about 10), to reduce the emittance and allow for more bunches. CESR has already operated for dedicated synchrotron radiation runs with betatron tunes as high as 14. At this point, though, it would be foolhardy to predict the luminosity gain.

4.5 Separate beam channels

In one variation of this idea the two beams would travel on parallel orbits defined by superconducting double-bore quadrupole magnets (Fig. 8) that would replace the present arc quadrupoles [45]. This would require modification also of the arc dipoles to widen the poles, and replacement of the ring vacuum chamber with a double chamber. The multiple pretzel orbit crossings would be eliminated, and the bunch frequency would be limited only by the minimum bunch separation implied by the ± 2 mrad crossing angle at the I.P. In a more ambitious version the two parallel orbits would be in separate magnets for most of the ring circumference [46]. The new arcs might use permanent magnets. In either scheme the possibility of storing a much greater number of beam bunches is almost sure to give CESR a luminosity capability greater than 10^{34}.

Prospects are good for CESR luminosities well in excess of B Factory levels.

5 Symmetric vs. Asymmetric Energies

5.1 Physics requirements

Since the poorly determined Kobyashi-Maskawa matrix elements are those involving the third generation b and t quarks, there is plenty of work left to do in B physics. Improvements in the existing measurements of B decay and mixing processes will help, but it is probably more important to widen the base of B interaction data in order to constrain better the models that are responsible for the rather large theoretical uncertainties (in italics in Table 1) in the extraction of the KM elements from the data. A symmetric energy e^+e^- collider is well suited for such measurements. What may not be so obvious is that a symmetric collider can also make a significant contribution to the measurement of CP violation in B decay.

In an e^+e^- collider with unequal beam energies the resulting boost of the $B^0\overline{B^0}$ production frame makes it easier to measure the time dependent CP violating asymmetries that tell us the angles α and β of the unitarity triangle. Asymmetric energy B Factories therefore have an advantage over symmetric energy colliders for this kind of measurement. Although CLEO at CESR could measure time dependences at the Υ(4S) with symmetric energies, making use of the silicon vertex detector resolution and the excellent definition of the vertical position of the beams, the number of events required would be about three times that needed when the $B^0\overline{B^0}$ pair is boosted by asymmetric beam energies (see appendix and [47]). So only if the asymmetric energy machines are not able to achieve high luminosities would a symmetric energy collider be able to compete in this kind of CP violation measurement.

In order to understand the origin of CP violation, however, it will be necessary to measure also the angle γ by observing time independent rate asymmetries, which do not benefit from the boost effect of an asymmetric energy B Factory. The experiments can be done either at a symmetric collider like CESR or at an asymmetric B Factory, provided there are large enough data samples for statistically significant CP violation effects. The measurements will require very high luminosities, perhaps as high as 10^{34} /cm^{2}s.

There is potentially even more excitement in the newly opened field of rare B decays, once we can achieve such luminosity levels. Branching fractions for loop decays are sensitive to high mass objects and are an alternative route to new physics that can compete with searches at the high energy frontier — the Tevatron and LHC. In measuring rare decay branching fractions there is no need to boost the collision, and a symmetric machine has no disadvantage.

Beyond CP violation studies and rare B decays, there are important physics topics that demand a center of mass that is at rest in the lab. For instance, the careful measurement of the forward-backward asymmetry in $e^+e^- \to \tau^+\tau^-$ would be unthinkable in a boosted frame with an asymmetric detector.

Figure 9: CESR pretzel beam orbits in the interaction region in the phase I head-on configuration and in the phase II angle-crossing geometry. Transverse horizontal dimensions are exaggerated by $> 10^2$ relative to longitudinal dimensions.

5.2 Energy asymmetry and luminosity capability

In the PEP2 asymmetric collider design the inequality in the beam energies is used to separate the beams after the collision, using magnets close to the interaction point on each side. The distance between the magnets, along with the $e^+ - e^-$ energy difference, place a lower limit on the spacing between each beam bunch and the following one. The PEP2 design luminosity depends on having a bunch frequency at the maximum allowed for beams of unequal energies colliding head-on. The luminosity cannot be increased by the straightforward expedient of increasing the numbers of bunches per beam.

In a high luminosity symmetric collider it is convenient to separate the two beams after the collision by simply colliding at a small angle (Fig. 9). The minimum longitudinal inter-bunch spacing allowed by the CESR ± 2 mr beam crossing corresponds to 180 bunches per beam, twenty times more than were used to achieve 3.2×10^{32} /cm^{2}s luminosity.

The simpler I.R. associated with symmetric energy collisions is an advantage in going for very high luminosities. For example, the extra magnetic focus contraints needed to make round beams at the intersection are compromised by the need for a low-β^* focus for two beams of different energies. So round beams would not have the same luminosity benefit for asymmetric machines that they may have for a symmetric collider.

Luminosities well beyond the 3×10^{33} /cm^{2}s level projected for the asymmetric colliders will probably be required to understand CP violation and exploit the physics of rare B

Figure 10: Sketch showing the principle of the CLEO ring imaging Cherenkow detector now under construction for high momentum particle identification.

decays. The chances of achieving this are better at a symmetric machine.

5.3 Effect of boost on detector performance

The CLEO detector is being upgraded to accommodate the charged particle tracking to the more intrusive phase III I.R. beam focusing elements, and to provide improved charged particle identification at high momenta [48] (see Fig. 7). The main drift chamber is being replaced by a new one that will have thinner, stepped end plates and a smaller outer radius. The tracking at low radius will be upgraded with a four-layer silicon detector. The new space outside the drift chamber will be occupied by a ring imaging Cherenkov system, employing a LiF radiator and a TEA photon converter (Fig. 10). Except for the particle identification techniques and the forward-backward asymmetric shapes, the BaBar and Belle detectors will be almost identical to the phase III CLEO detector. But asymmetric energies may be a disadvantage for most measurements.

Particle identification is crucially important for identifying rare B decay modes in the presence of copious backgrounds. For CP violation measurements one will have to distinguish $\pi^-\pi^+$ and $K^-\pi^+$. In the BaBar and Belle experiments the momenta of the B decay secondaries, which are less than 2.8 GeV in the $\Upsilon(4S)$ frame, are boosted as high as 4 GeV/c. This makes particle identification more difficult. The optimal Cerenkov medium is less dense (producing less light) while the required accuracy in velocity selection is tighter. Thus BaBar and Belle cnnot make use of the fast ring-imaging Cerenkov scheme under construction for

CLEO [48] (Fig. 10). They have to rely on the more risky, untried DIRC technique [8] or accept the limited selectivity of aerogel [9]. Good vertex resolution cannot help to distinguish a K^+ from a π^+.

6 The CESR Program for the New Millenium

The primary goals for the CESR facility and the CLEO experiment are clear.

1. Continue important, productive research in heavy quark and lepton physics as long as it is interesting as a window on the standard model and beyond: CP violation, rare loop decays, leptonic B decays, tagged B studies, charmed meson and baryon spectroscopy, charm decays, rare τ decays, and so on.

2. Continue to increase CESR luminosity, not only to advance the CESR/CLEO HEP goals but also to serve the worldwide accelerator community as a testbed for innovations.

3. Continue to serve the US high energy physics program by providing a user-friendly facility for faculty, post-docs, and graduate students from many universities to pursue world-class research in particle physics.

4. Continue to provide, as a byproduct, high intensity x-ray beams for the hundreds of users of the Cornell High Energy Synchrotron Source (CHESS).

Looking ahead, we can see an exciting program for the next decade.

1995-1997: CESR and CLEO exploit the phase II upgrade of CESR luminosity ($\int \mathcal{L}dt \sim 6$ fb^{-1}/yr) and the new CLEO silicon tracker to advance the study of rare B decays and the other topics in heavy quark and lepton physics, while preparing for the phase III installation of the superconducting I.R. quads and rf cavities and the new CLEO tracking and particle ID hardware.

1998-2002: CESR and CLEO continue to enjoy a monopoly at the $e^+e^- \to b\bar{b}$ threshold, reaping the benefits of the phase III upgrade ($\int \mathcal{L}dt \sim 15$ fb^{-1}/yr) to build up the B decay data base necessary for a quantitative understanding of later CP violation results, meanwhile working on new ideas to increase the luminosity beyond 30 fb^{-1}/yr.

2003-20xx: CESR and CLEO take a leading role in the understanding of CP violation and physics beyond the standard model, making use of the world's highest luminosity ($\sim$ 100 fb^{-1}/yr?). When and if the physics at the $b\bar{b}$ threshold becomes no longer exciting, the Cornell Laboratory of Nuclear Studies will look for a new challenge.

APPENDIX

Mixing-Mediated CP Asymmetries at a Symmetric Collider

The mean decay length of B's from an $\Upsilon(4S)$ produced at rest is only

$$\gamma\beta c\tau = \sqrt{(M_{4S}/2m_B)^2 - 1} \;\times\; c\tau = 30\ \mu\text{m}.$$

The beams in CESR annihilate in a region of r.m.s size $\delta x \times \delta y \times \delta z = 600 \times 8 \times 18000\ \mu\text{m}^3$. In the vertical the annihilation point is tolerably well defined relative to the decay length and the vertex measurement resolution. The height $\overline{y}$ of the midpoint between the two measured decay vertices, y_f and y_{tag}, measures $t_f - t_{tag}$:

$$\overline{y} = \frac{y_f + y_{tag}}{2} = \frac{1}{2}\cos\chi \cdot \gamma\beta c(t_f - t_{tag}) + y_{beam}. \tag{7}$$

where χ is the angle between the momentum of the B_f and the upward y axis.

The mean value of $t_f - t_{tag}$ is obtained by integrating equation (2):

$$\langle t_f - t_{tag}\rangle = \frac{1}{N}\int\int(t_f - t_{tag})\frac{d^2N}{dt_f dt_{tag}}dt_f dt_{tag} = \frac{2x_d q\tau}{(1+x_d^2)^2}\sin 2\phi. \tag{8}$$

From equations (7) and (8) it is clear that whether $\overline{y}$ will tend to be above or below the beam line will depend on two signs, the charge of the tag q and the sign of $\cos\chi$, that is, whether the B that decays to ψK_S goes up or down. Combining the two signs and defining a parameter for each event,

$$k = q\frac{\cos\chi}{|\cos\chi|} = \pm 1, \tag{9}$$

we can subdivide the data set into two subclasses, depending on whether $k = +1$ or $k = -1$. If the two $\overline{y}$ means differ, CP is violated:

$$\langle\overline{y}\rangle_k = k\frac{9}{16}\frac{x_d}{(1+x_d^2)^2}\gamma\beta c\tau\sin 2\phi + y_0. \tag{10}$$

The measured difference $\Delta = \langle\overline{y}\rangle_{+1} - \langle\overline{y}\rangle_{-1}$ between the average $\overline{y}$ values for the two event subclasses will then be a direct measure of the CP violation parameter $\sin 2\phi$:

$$\sin 2\phi = \frac{8}{9}\frac{(1+x_d^2)^2}{x_d}\frac{\Delta}{\gamma\beta c\tau} = \frac{\Delta}{10.3\ \mu\text{m}}. \tag{11}$$

A Monte Carlo simulation of a CLEO measurement of $\sin 2\beta$, using the time evolution of tagged $B \to \psi K_S$ decays [47], shows that the separation Δ between the weighted averages of the two distributions can be measured to an r.m.s. accuracy of

$$\delta\Delta = \frac{34\ \mu\text{m}}{\sqrt{N}}. \tag{12}$$

Combining this with equation (11) we can compute the r.m.s. accuracy in the measurement of $\sin 2\beta$ as a function of the number of measured tagged events:

$$\delta \sin 2\beta = 3.3/\sqrt{N}. \tag{13}$$

For the asymmetric B Factory the measurement sensitivity is given by $\delta \sin 2\beta = 2.0/\sqrt{N}$. That is, the penalty for not boosting the B's is a factor of about three in the number of events required.

This is the process for which the asymmetric energy B Factories were designed. However, taking advantage of good vertex resolution and small vertical beam size, a symmetric machine could make the same measurement, even at the $\Upsilon(4S)$, but it would require higher luminosities than the measurement with asymmetric energies. Only if the asymmetric machines were delayed in reaching high luminosities, or if non-standard physics made the effect anomalously large, would there be a chance for a symmetric collider to contribute significantly to this measurement.

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