Observing CP Violation at a Symmetric B Factory

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Abstract

While it has generally been assumed that it is necessary to measure the time-dependence of B meson decays to measure CKM phases, several recent theoretical analyses suggest that at least one of the angles of the unitarity triangle can be extracted from rate measurements alone. Therefore, these measurements could be made at a symmetric e^+e^- collider operating at the $\Upsilon(4s)$ where there are well established techniques for obtaining excellent signal to background in a variety of B meson decay channels. The only candidate for a symmetric B Factory is CESR, the Cornell Electron Storage Ring. The status and future plans of CESR and of the CLEO detector, which operates at the single CESR interaction region, are reviewed. It will be shown how measurements of the magnitudes of all CKM matrix elements can be made by CLEO. The potential for measuring one of the angles of the unitarity triangle is also discussed.

Introduction

Direct CP violation can be observed by measuring a rate asymmetry. In $B^{\pm} \to K^o\pi^{\pm}$ decays, for example, the rate asymmetry A is given by;

$$A = \frac{\#(K^o\pi^+) - \#(K^o\pi^-)}{\#(K^o\pi^+) + \#(K^o\pi^-)} \tag{1}$$

Unfortunately, this generally requires the production of a very large number of B mesons. For a decay mode with branching ratio $\mathcal{B}$ and detection efficiency ε, the number of $B\bar{B}$ pairs, $N_{B\bar{B}}$, that need to be produced in order to observe a 4 standard deviation effect in A is given by: $N_{B\bar{B}} = 16/\mathcal{B}\varepsilon A^2$. Therefore, for $\mathcal{B}\varepsilon = 10^{-5}$, some 160 million $B\bar{B}$ pairs must be produced in order to observe a 10% asymmetry.

This paper will describe what a symmetric B Factory is, how it can be achieved, and what measurements can be made at such a facility with regards to the Cabibbo-Kobayashi-Maskawa (CKM) matrix – the standard model explanation of CP violation.

The Need for Luminosity

A symmetric B Factory is an electron-positron collider with $E_{e^+} = E_{e^-} = m(\Upsilon(4s))/2$ and with a luminosity of at least $3 \times 10^{33}\ cm^{-2}s^{-1}$. To give a feel for what this means in terms of the number of B mesons produced, consider the hadronic e^+e^- cross-section in the Υ mass region, as shown in Figure 1. All the Υ resonances lower in mass than the $\Upsilon(4s)$ are below threshold for producing B mesons.

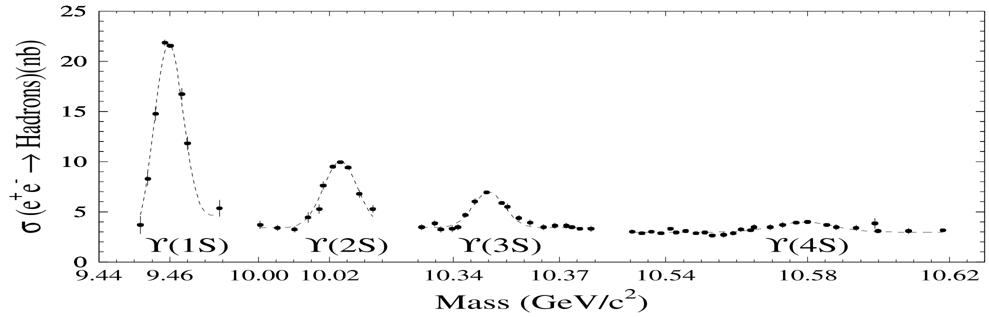


Figure 1: The e^+e^- cross-section in the Υ mass region.

Both the $c\bar{c}$ and $b\bar{b}$ cross-sections at the $\Upsilon(4s)$ are about a nanobarn and for many decay channels of the B meson it is difficult to get a clean sample because of the large charm background (and, to a lesser extent, from $u\bar{u}$, $d\bar{d}$, and $s\bar{s}$ production). It is for this reason that experiments performed at the $\Upsilon(4s)$ take some amount of data just below $B\bar{B}$ threshold (generally refered to as continuum) so as to be able to quantify the non-$B\bar{B}$ contribution. For the CLEO-II experiment, this fraction of on-resonance to continuum data is about 2:1. Hence, every fb^{-1} of data contains around 660,000 $b\bar{b}$, 1,000,000 $c\bar{c}$, and 800,000 $\tau^+\tau^-$ pairs. Furthermore, a b quark decays essentially 100% of the time to a charm quark so about 3.2 million charmed particles are produced per fb^{-1}. CLEO-II has collected $\sim 3\ fb^{-1}$ of data to date.

It is clear from these numbers why very high luminosity is required to study CP violation in the B system. Assuming the same on-resonance to continuum fraction as used by CLEO-II and reasonable machine efficiency, a luminosity of $3 \times 10^{33}\ cm^{-2}s^{-1}$ corresponds to 30 fb^{-1} or 20 million $B\bar{B}$ pairs per year.

CESR, CLEO, and Physics at the $\Upsilon(4s)$

The Cornell Electron Storage Ring, CESR, is currently the highest luminosity collider in the world[1]. The present and projected CESR luminosities are given in Table 1. CESR operates in so-called pretzel mode. That is, the electrons and positrons in the machine do not follow the central beam trajectory through the centre of the quadrupole magnets but rather electrostatically distorted orbits. The desire is to keep the two beams separated in space everywhere except at the interaction point. The method proposed to get to the luminosity levels stated in Table 1 is to increase the current in the machine by going from seven bunches to nine closely spaced trains of 3 to 5 bunches. This bunch train topology necessitates having the beams collide with a crossing angle of about 2 $mrad$ in order to separate the parasitic crossings near the interaction point.

CESR has been successfully run this year both with nine bunches in the machine and with a crossing angle so the numbers in Table 1 are not unrealistic.

Table 1: CESR Luminosity Projections

Year	Luminosity ($10^{32}/cm^2/sec$)
1994	2.5
1995	6.0
1998	10.0

The CLEO-II detector, which functions in the single CESR interaction region, measures both neutral and charged particles with excellent resolution and efficiency[2]. In particular, the π^o reconstruction efficiency and momentum resolution are about half that of charged pions because of the excellent photon energy resolution of the CsI calorimeter. This superb neutral particle detection capability, coupled with the record luminosity performance of CESR, has allowed CLEO to study a vast array of new charm and B decay channels. Charged particle tracking will be upgraded in the near future with the installation of a silicon microstrip detector with double-sided readout and a new central drift chamber is under construction[1]. Finally, there are also plans to improve the particle identification capabilities of the detector.

As well as being a source of large, clean samples of charmed particles and τ leptons, a symmetric e^+e^- collider operating at the $\Upsilon(4s)$ offers many advantages for doing B physics. The $\Upsilon(4s)$ is just above threshold for $B\bar{B}$ production so there are no B^* or B_s mesons or Λ_b baryons produced nor are there any other particles produced along with the $B\bar{B}$ pair. The energy of the B (or $\bar{B}$) is therefore exactly equal to the beam energy. Using this constraint in the calculation of the invariant mass of a B candidate (the so-called 'beam constrained' mass) leads to a B mass resolution of about 2.5 MeV, an order of magnitude better than would be obtained from simply summing the four-momenta of the decay products[3]. The average B momentum of 325 MeV is very small relative to its 5.279 GeV mass. Therefore, $p_B \approx 0$ is a good approximation allowing for the use of missing mass and partial reconstruction techniques. Finally, since the B and $\bar{B}$ are produced nearly at rest, there is no well-defined jet axis in the event and hence the decay products of the B and $\bar{B}$ mesons will be randomly distributed throughout the volume of the detector. This is not the case for continuum events which tend to align along a jet axis. This difference in event topology can be exploited to select $B\bar{B}$ events and suppress continuum events.

Measuring the CKM Matrix

Since the unitary CKM matrix is the standard model description of CP violation, it is crucial for experimentalists to measure both the amplitudes and phases of the elements of the matrix. The unitarity of the matrix results in relations like $V_{ud}V_{ub}^*+V_{cd}V_{cb}^*+V_{td}V_{tb}^* = 0$. This equation is the source of the famous 'unitarity triangle' when the products of elements are represented by vectors in the complex plane[4]. Unitarity also leads to the experimentally testable proposition that the sum of the squares of the elements in any row or column must add up to 1 (e.g., $|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 1$).

What follows is a brief explanation of how the magnitude of each element can, at least in principle, be measured at a symmetric B Factory. The list also serves to illuminate the richness of the physics that can be performed at such a facility. The Cabibbo sector of the matrix is discussed first.

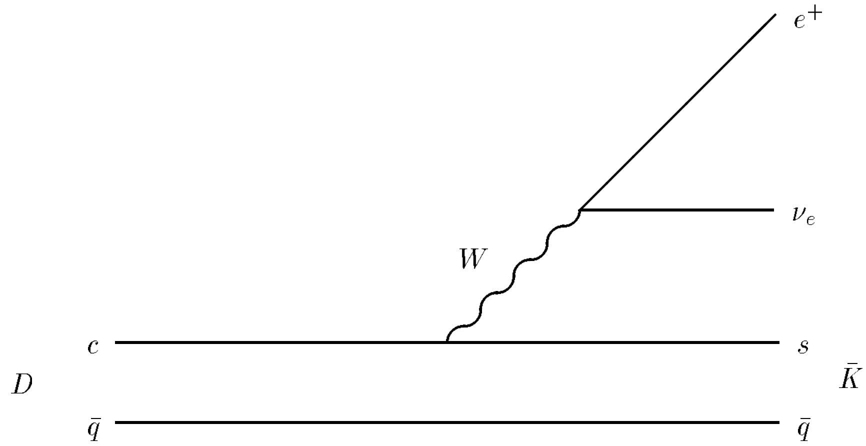
$|V_{ud}|$ • The $\tau^- \to \pi^- \nu_\tau$ width (neglecting short-distance loop enhancements[5]) is given by;

$$\Gamma = |V_{ud}|^2 f_\pi^2 \frac{G_F^2 m_\tau^3}{16\pi} \left(1 - \frac{m_\pi^2}{m_\tau^2}\right)^2 \tag{2}$$

and so V_{ud} could be extracted from a measurement of the branching ratio for this process. Unfortunately, even with the the vast increase in precision in m_τ and τ_τ, there is still the problem of independently getting a measurement of f_π. If the decay constant could be calculated from theory with enough precision, either analytically or on the lattice, then this is a viable method for extracting a CKM matrix element.

$|V_{us}|$ • Again the one-prong τ decay can be used but now with a kaon instead of a pion in the final state. There is still the problem of independently obtaining a decay constant – in this case, f_K. However, the ratio $\mathcal{B}(\tau^- \to K^- \nu_\tau)/\mathcal{B}(\tau^- \to \pi^- \nu_\tau)$, which yields a measurement of $(f_K/f_\pi)|V_{us}|/|V_{ud}|$, offers some advantages. On the experimental side, most of the systematic errors associated with tracking and trigger efficiencies cancel as do those from the uncertainties in τ_τ and m_τ. Only the particle identification capabilities of the detector remain as the main source of experimental systematic error. On the theoretical side, the predictions of ratios of decay constants are generally more precise than are the predictions for a particular decay constant.

$|V_{cs}|$ • This CKM element can be extracted either from $D_s^+ \to \mu^+ \nu_\mu$, where the relevant decay constant is f_{D_s}, or from semileptonic D meson decay. The Feynman diagram for $D \to \bar{K} e^+ \nu_e$ is shown below;



where $\bar{q}$ refers to either a $\bar{u}$ or a $\bar{d}$ quark. From a sample of over 2500 reconstructed $D^o \to K^- e^+ \nu_e$ events, CLEO-II finds[6]: $f_+^K(0)|V_{cs}| = 0.77 \pm 0.01 \pm 0.03$. Again it is necessary to get input from theory, in this case the form factor f_+^K, to extract a CKM matrix element.

$|V_{cd}|$ • In analogy to the extraction of V_{us}/V_{ud} from τ decays, the ratio $\mathcal{B}(D \to \pi l \nu)/\mathcal{B}(D \to K l \nu)$, which is proportional to $|f_+^\pi(0)/f_+^K(0)|^2 |V_{cd}/V_{cs}|^2$, results in the cancellation of most of the systematic errors. Using the $D^{*+} \to D^+ \pi^o$ decay chain to reduce combinatoric backgrounds, CLEO-II measures $\mathcal{B}(D^+ \to \pi^o l \nu)/\mathcal{B}(D^+ \to K_s l \nu)$ which yields the result[7]:

$$\left|\frac{f_+^\pi(0)}{f_+^K(0)}\right|^2 \left|\frac{V_{cd}}{V_{cs}}\right|^2 = 0.085 \pm 0.027 \pm 0.014 \tag{3}$$

$|V_{cb}|$ • This is the one case where, at least for $B \to D^* l \nu$ decays, the form factor can be predicted with good precision. The CLEO-II result[8] is $|V_{cb}| = 0.0351 \pm 0.0019 \pm 0.0020 \pm 0.0014$.

$|V_{ub}|$ • Unfortunately, the theoretical techniques which allow for a precise measurement of V_{cb} are not applicable for heavy to light quark transitions like $b \to u$. Such decays have been observed by CLEO-II by measuring an excess of high momentum leptons beyond the kinematic limit for $b \to c$ transitions[9]. The error on the result of $|V_{ub}|/|V_{cb}| = 0.08 \pm 0.02$ reflects the theoretical uncertainty in the shape of the lepton momentum spectrum. Only upper limits have been derived from the exclusive reconstruction of $B \to X_u l \nu$ decays where X_u represents π^-, ρ, or ω. A measurement of the $B \to \tau\nu$ branching fraction would yield $f_B|V_{ub}|$. The CLEO-II limit for this decay is still an order of magnitude above the standard model prediction.

$|V_{tb}|$, $|V_{ts}|$, $|V_{td}|$ • These elements always appear in pairs since they are present in B decays through loop processes. For example, calculations involving the box diagrams which allow for $B^o - \bar{B}^o$ mixing give an expression for the difference between mass eigenstates which depends on the product of $|V_{tb}|$ and $|V_{td}|$ as well as the top quark mass and the B decay constant[10]. The other B decay process inolving a top quark loop is the famous electromagnetic 'penguin' diagram[11] which leads to final states like $K^*\gamma$. The ratio $|V_{td}|/|V_{ts}|$ can be extracted from a measurement of $\mathcal{B}(B^o \to (\rho,\omega)\gamma)/\mathcal{B}(B^o \to K^*\gamma)$. CLEO-II combines the result for $\mathcal{B}(B \to K^*\gamma)$ with upper limits on $B \to \rho\gamma$ and $B \to \omega\gamma$ decays to get $|V_{td}|/|V_{ts}| < 0.6$.

Measuring a CKM Phase using Rates

To observe CP violation through a rate difference requires there to be two decay diagrams leading to the same final state. For example, the $B^\pm \to K^\pm \pi^o$ decay can occur either through the $b \to u$ external spectator diagram with the W fragmenting to $s\bar{u}$ or through a $b \to s$ $(u\bar{u})$ gluonic penguin. The spectator and penguin amplitudes can be represented by $S = se^{i\delta_s} V_{ub} V_{us}^*$ and $P = pe^{i\delta_p} V_{tb} V_{ts}^*$, where δ is a strong phase. The corresponding CP conjugate amplitudes are $\bar{S} = se^{i\delta_s}V_{ub}^*V_{us}$ and $\bar{P} = pe^{i\delta_p}V_{tb}^*V_{ts}$. The CP violating rate difference will then be;

$$\Gamma - \bar{\Gamma} = |S+P|^2 - \left|\bar{S}+\bar{P}\right|^2 = 4sp\sin\left(\delta_s - \delta_p\right)\Im\left(V_{ub}V_{us}^*V_{tb}^*V_{ts}\right) \tag{4}$$

This illustrates the three things needed to be able to observe CP violation in a rate difference: 1) two interfering amplitudes of comparable magnitude (i.e., s and p), 2) different strong phases, and 3) different weak phases.

Two methods have been proposed for measuring the angle γ ($\equiv ArgV_{ub}^*$) of the unitarity triangle through measurements of charged B meson decay rates. One method requires measuring the $B^\pm$ to $\pi^\pm K^o$, $\pi^o K^\pm$, and $\pi^\pm\pi^o$ branching ratios[4]. The branching ratios are predicted to be on the order of 10^{-5}. The sum of $\mathcal{B}(B^o \to K^+\pi^-)$ and $\mathcal{B}(B^o \to \pi^+\pi^-)$ was measured by CLEO-II to be $(2.4^{+0.8}_{-0.7} \pm 0.2) \times 10^{-5}$. It is estimated that around 100 events in each mode are needed to measure γ to $\pm 10^o$ which again, with reasonable efficiencies, requires a data sample of some 10^8 B mesons. The main experimental difficulty involves having good enough particle identification capabilities so as to be able to distinguish $B^\pm \to K^\pm\pi^o$ from $B^\pm \to \pi^\pm\pi^o$ decays. CLEO-II has just over 2σ $K \leftrightarrow \pi$ separation for momenta above 2 GeV although there are plans to improve this. It is also necessary to know that the detector has equal response to negatively and positively charged tracks.

The second method for measuring γ was proposed by Gronau and Wyler and makes use of the remarkable fact that the $B^\pm$ meson can decay to both $D^oK^\pm$ and $\bar{D}^oK^\pm$[12]. The D which decays into a flavour non-specific final state like K^+K^- is then the coherent superposition of the D^o and $\bar{D}^o$ states (i.e., $D_\pm \equiv 1/\sqrt{2}(D^o \pm \bar{D}^o)$ where D_+ (D_-) is even (odd) under CP). D_+ final states include K^+K^- and $\pi^+\pi^-$ while the D_- decays to, for example, $K_s\pi^o$ and $K_s\eta$. The final results are relationships between branching ratios like;

$$\begin{aligned} 2\mathcal{B}(B^+ \to D_+K^+) &= \mathcal{B}(B^- \to D^oK^-) + \mathcal{B}(B^- \to \bar{D}^oK^-) \\ &+ 2\sqrt{\mathcal{B}(B^- \to \bar{D}^oK^-)\cdot\mathcal{B}(B^- \to D^oK^-)}\cos(\gamma+\delta) \end{aligned}$$

where δ is the difference in strong phases. In this case the strong phase difference can be zero and it would still be possible to measure γ. It is also possible to use the $D^{*o}K^-$, D^oK^{*-}, and $D^{*o}K^{*-}$ final states which may have different strong phase shifts but will have the same CP violating phase.

The experimental difficulties again include needing good enough particle identification to be able to separate the D^oK^- signal from the CKM favoured $D^o\pi^-$ final state. There is also a potentially problematic background from continuum $c\bar{c}$ production where a D^o is produced in the charm quark fragmentation while a K^+ results from the weak decay of the $\bar{c}$ fragmentation product. On the other hand, it may be possible to improve the signal to noise in the future since the addition of a silicon detector allows for the detection of separated D decay vertices.

Conclusions

The CLEO-II experiment is already making high precision measurements which test every aspect of B meson decay. There are plans for major upgrades to the detector including better particle identification capability and more precise tracking. CESR has plans to increase the luminosity to at least $10^{33}\ cm^{-1}s^{-1}$ before the end of the century. Measurements of B decay rates at such a 'Symmetric B Factory' will nicely complement the time-dependent measurements that can be performed at the Asymmetric B Factories now under construction. Perhaps both will be needed to finally uncover the secret of CP violation.

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