EXPERIMENTAL ASPECTS OF B PHYSICS *

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1. Introduction

The first experimental evidence for the existence of the b quark came in 1977 from an experiment at FNAL[1] in which high energy protons were scattered off of hadronic targets. A broad resonance, shown in Fig. 1, was observed in the plot of the invariant mass of muon pairs seen in a double armed spectrometer. The width of the resonance was greater than the energy resolution of the apparatus and the data were interpreted as the three lowest lying quark anti-quark bound states of a new quark flavor: b flavor, which stands for either beauty or bottom. These $b\bar{b}$ bound states were called the Υ, Υ', and Υ''.

When the $c\bar{c}$ bound state, the J/ψ, was discovered, it was found simultaneously in proton-nucleus collisions at Brookhaven[2] and at SPEAR[3] in e^+e^- collisions. However, it took a year for the e^+e^- storage ring, DORIS, to confirm the Υ discovery,[4] and it was still 2 years later that the then new e^+e^- storage ring at Cornell, CESR, also observed the $\Upsilon(1S)$, $\Upsilon'(2S)$, $\Upsilon''(3S)$ states and discovered a fourth state, $\Upsilon'''(4S)$.[5] Both storage rings were easily able to resolve the states of the Upsilon system. Figure 2 shows the observed cross section at CESR versus energy in the Upsilon region, and although the apparent width of the 3 lower lying resonances is due to the machine energy spread, the true width and the leptonic width of the Υ could be inferred from the peak cross section and the leptonic branching ratio.[6] The leptonic width is proportional to the square of the quark charges inside the Upsilon and the b quark was inferred to have charge 1/3.

The $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ and the other bound states of the $b\bar{b}$ system are interesting objects. By studying the energy splitting and decay modes (much like an atomic physicist studies the spectrum of an atom) one learns a great deal about the QCD potential that binds the quarks. However, our interest will be in center of mass energies of the $\Upsilon(4S)$ and beyond, where there is sufficient energy to make B mesons: mesons made from a b quark and a light quark, and which carry the b quantum number.

The width of the $\Upsilon(4S)$ as shown in Fig. 2, is about 24 MeV, which is greater than the 2 MeV energy spread of CESR. The $\Upsilon(4S)$ is broad because

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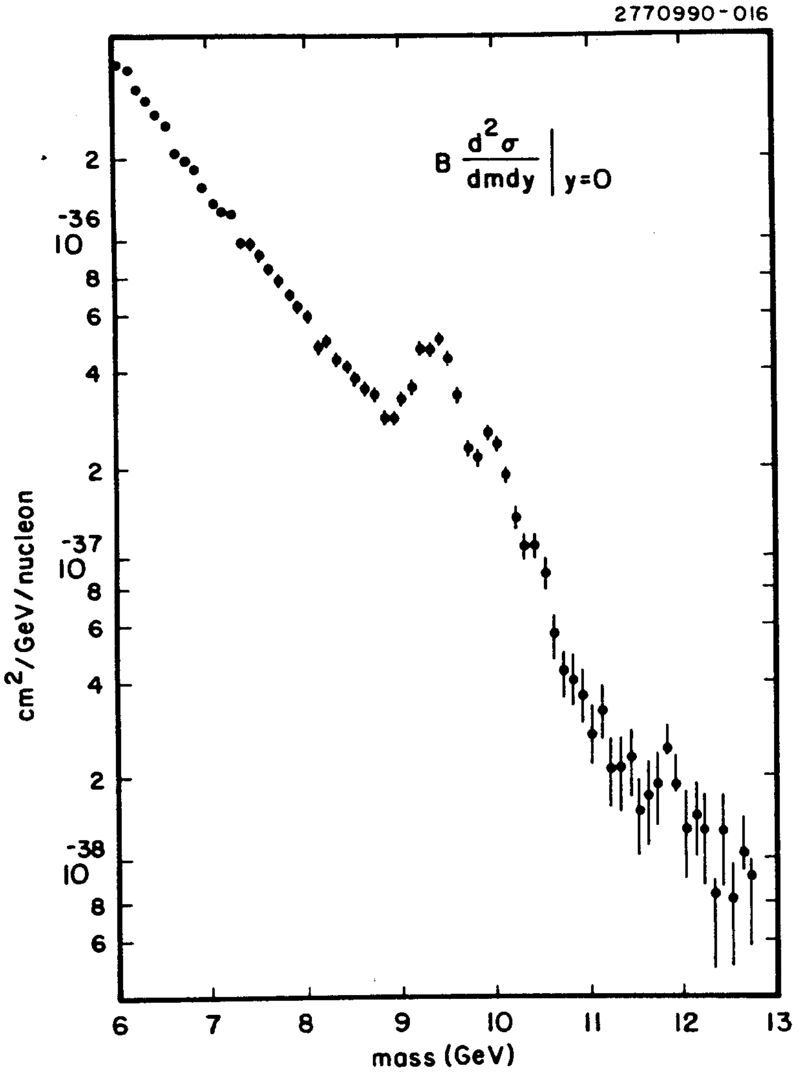

Figure 1. The invariant mass of muon pairs produced in proton nucleus collisions showing the Upsilon resonances.

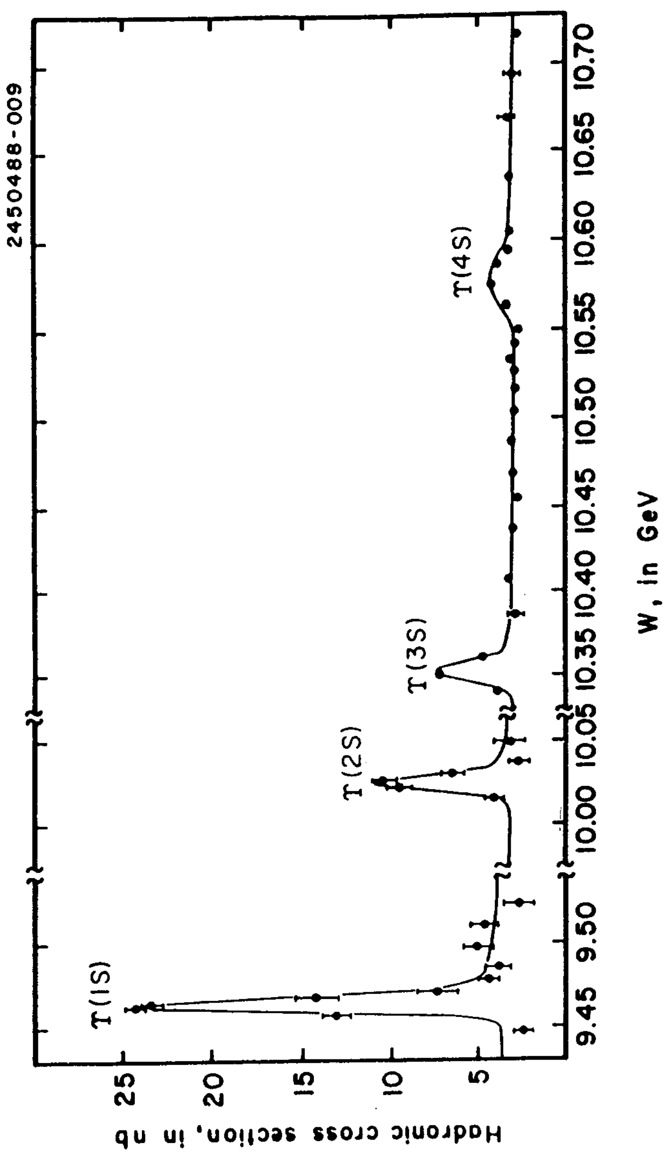

Figure 2. The hadronic cross section as a function of center of mass energy in the Upsilon energy region from CLEO.

it can decay directly into a pair of B mesons. A B meson produced at the $\Upsilon(4S)$ is the lowest mass particle containing a b quark and so in order for it to decay, the flavor of the b quark must change. It can turn into a c quark for example, and that means the B meson must decay weakly since both the strong and electromagnetic interactions conserve flavor; only the weak interactions can change flavor.

We can use the decays of the B mesons to probe the structure of the weak interactions of quarks. What we will find is that in large measure, we will be probing the Cabibbo-Kobayashi-Mashawa (CKM)[7] matrix. As is discussed in detail elsewhere,[8] the eigenstates of the weak interactions are not the same as the flavor eigenstates of the strong interactions. In quantum mechanical terms, flavor is a symmetry of the strong interactions, so the strong interaction is diagonal on the quark flavor basis. The weak interactions are diagonal on a different basis and there is some unknown and undetermined transformation matrix, the CKM matrix, that relates the two bases.

This is not conceptually different from the problem faced when solving the Zeeman effect or the Stark effect for the hydrogen atom. The two perturbations have different symmetries, they have different conserved quantum numbers, and therefore they are diagonal on different basis sets. The perturbed wave functions exhibit the symmetry of the Hamiltonian. The different bases can be related by a linear transformation from first principles. In the case of quark mixing, unfortunately, we cannot construct the transformation matrix from first principles. A large part of our task, therefore, in studying the weak interactions of quarks, is to determine the 3×3 matrix that relates the eigenstates of the weak interaction to the flavor eigenstates of the strong interactions.

The organization of these notes will be as follows: first I will discuss the basic properties of the B mesons: how they are produced and where; basic features of B decay; and basic properties of the mesons such as mass, lifetime, and spin. In the next section, I will concentrate on the semi-leptonic decays of the B mesons, which is a very rich field from which a great deal of information has been gleaned, and I will discuss the measurements of the CKM matrix elements that can be made with B mesons. The final chapter will try to look into the future. With new experiments at LEP and SLC, we are starting to learn how the b quark couples to the Z^0. Furthermore with the turn on of CLEO II at CESR, we hope to have much greater power to probe B decays. I will end with a brief discussion of some of the proposed experiments that hope to find the holy grail of B meson physics: CP violation. Let me make a disclaimer. Since the emphasis of these notes is meant to be pedagogical, I am not attempting to give an exhaustive review. I will not mention every result on a particular topic, but tend to concentrate on one or two particular examples.

2. Basic Properties of B Mesons

A. Production of B Mesons

The mass of the bottom quark is approximately 5.0 GeV, and technically, there are four B mesons: $B_u = b\bar{u}$, $B_d = b\bar{d}$, $B_s = b\bar{s}$, $B_c = b\bar{c}$. The first two of these, referred to as B^- and $\bar{B}^0$, are the only established B mesons. There is indirect evidence for the B_s although it is not overwhelming. I will discuss, almost exclusively, properties of the low mass mesons: B^- and $\bar{B}^0$.

B mesons are produced at all e^+e^- machines with a center of mass (CM) energy greater than twice the mass of the B meson or $\sqrt{s} \approx 10.56$ GeV. The most copious producers of B meson physics have been the CLEO detector operating at the storage ring CESR at Cornell and the ARGUS detector operating at DORIS at DESY in Germany. These experiments take the bulk of their data on the $\Upsilon(4S)$ ($\sqrt{s} = 10.58$ GeV) which is just above threshold for B meson production. The $\Upsilon(4S)$ decays almost exclusively to pairs of B mesons. ARGUS and CLEO have accumulated roughly 250,000 $\Upsilon(4S)$ decays or 500,000 B mesons each. The mass of the meson is about 5280 MeV and the Q of the reaction is only $10.580 - 2 * 5.280 = 20$ MeV, so there is not any room for an extra pion. Both these experiments produce a pair of B mesons nearly at rest ($\beta = .06$) and nothing else. The advantage of this will become evident when we talk about reconstruction of B mesons. The peak cross section at the $\Upsilon(4S)$ is about 1.2 nb sitting on approximately 3.5 nb of what we call the continuum background, which is made of events where e^+e^- annihilate and make a light quark pair. The advantages of the $\Upsilon(4S)$ are that a B and a $\bar{B}$ are produced, with no other particles, and the signal cross section and the signal to background ratio are high. The biggest disadvantage of the $\Upsilon(4S)$ is that the B's are produced essentially at rest. The average B travels 20 μm from its production point before decaying, and it decays isotropically. (The B has spin 0.) The decay products of the two B mesons that are produced overlap, and the combinatoric background to sorting out which particle belongs to which B is substantial.

The other e^+e^- machines that make or have made B mesons are PEP, PETRA, TRISTAN, SLC and LEP. At PEP and TRISTAN energies one has the disadvantage that both the cross section to produce B's and the ratio of signal to background are much lower than at CESR and DORIS. The cross section to produce b quarks is approximately .03 nb at $\sqrt{s} = 29$ GeV, and $b\bar{b}$ events make up about 10% of all hadronic events. The big advantage of these machines is that the B's are produced with a substantial boost. At PEP and PETRA, the average B meson travels almost a millimeter before it decays. That is a long distance on the scale of vertex detector accuracies, and both PEP and PETRA have done nice B physics by identifying B events using separated vertices. Most importantly, they have been able to use the measured flight path of the B to derive its lifetime: a measurement which the $\Upsilon(4S)$ machines cannot do.

- SLC and LEP have the advantage that PEP and PETRA do of producing B's with substantial boost. The cross section to produce a pair of b quarks is a substantial 6 nb; larger, in fact, than the production cross section at the $\Upsilon(4S)$. Signal to background is more of a problem since many other particles are produced at the Z resonance, but I expect that the LEP and SLC experiments will contribute alot to B physics in the next few years.

Of course, proton machines can produce B's also. In fact, proton machines such as the $Sp\bar{p}S$ and the Tevatron have produced more b quarks and B mesons than all the other machines put together. The cross section to produce a $b\bar{b}$ pair, which is dominated by gluon fusion, is approximately $10\mu b$ (that is 4 orders of magnitude greater than the cross section at the $\Upsilon(4S)$) at $\sqrt{s} = 630$ GeV and goes up to as high as $50\mu b$ at 2 TeV.[9] With this enormous cross section why haven't we seen more b physics from $p\bar{p}$ colliders? There are two problems. The most basic and fundamental is that while the cross section to produce a pair of b quarks is large, the total inelastic cross section is enormous so that $\sigma_{b\bar{b}}/\sigma_{tot} \sim 1/1000$ at the Tevatron. Extracting bottom physics from everything else going on is a tremendous challenge. The second obstacle to B physics at $p\bar{p}$ colliders is that experiments such as CDF and UA1 are designed to do physics with high p_t leptons; leptons with a minimum of several GeV of momentum transverse to the beamline where Z's and W's are. To have good acceptance for leptons from b decays, one must be able to accept tracks with quite low $(\sim 1\ GeV)p_t$. I mention leptons specifically since in order to separate b physics from the enormous background, one invariably needs to use leptons in the final state. Furthermore, CDF, for example, has no particle identification for $\pi - K$ separation, and no vertexing capability which the fixed target charm experiments have taught us can be very useful. This will be dramatically improved in the next collider run with the addition of a silicon vertex detector.

Table I
Summary of experimental techniques for B physics

E_{CM}	N_b/Experiment to date	$\sigma_{b\bar{b}}$	$\sigma_{b\bar{b}}/\sigma_{had}$	+/−
10.58 GeV e^+e^-	500,000	1.2 nb	1.2/3.5	$+\sigma(b\bar{b}), S/B$ $+\Upsilon(4S) \rightarrow B\bar{B}$ +/− B's at rest
29 GeV e^+e^-	15,000	.03 nb	1/10	$+\gamma\beta c\tau$ $-S/B, \sigma(b\bar{b})$ $-b\bar{b}X$
92 GeV e^+e^-	15,000	6 nb	1/5	$+\gamma\beta c\tau$ $+S/B, \sigma(b\bar{b})$ $-b\bar{b}X$
630 GeV $p\bar{p}$	10^8	$10\mu b$	1/5000	$+\gamma\beta c\tau$ $+\sigma(b\bar{b})$ $-S/B$
1.8 TeV $p\bar{p}$	$5 * 10^8$	$50\mu b$	1/1000	$-b\bar{b}X$ − Trigger

This is not to say that B physics is impossible at proton machines. In fact, as shown in Fig. 3., CDF can reconstruct B mesons in the highly supressed (but very clean) channel $B \rightarrow \psi K^-$.[10] They have 16 ± 6 such events (compared to 17 from CLEO and ARGUS and combined). They do have more background, but it is an impressive achievement.

Table I gives a summary (not meant to be exhaustive) of the various experimental techniques for B physics and some of the advantages and disadvantages of each.

Before proceeding to discuss how B mesons decay, now that we know how to produce them, I want to discuss the production of B mesons at the $\Upsilon(4S)$ in a little more detail.

We know that the $\Upsilon(4S)$ decays into both charged and neutral B mesons $(B^-, \bar{B}^0)$. What is the fraction of charged mesons produced relative to neutral?

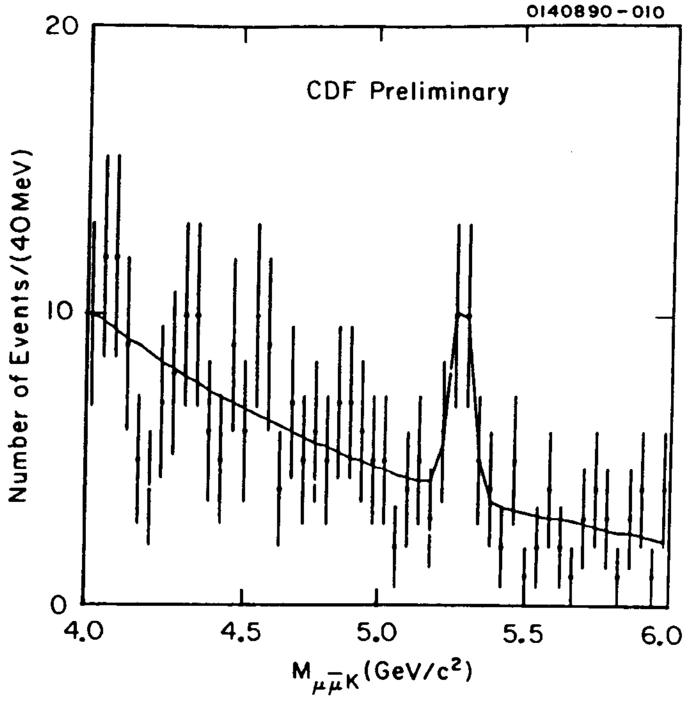

Figure 3. CDF data for $B^- \to J/\psi K^-$.

Are equal numbers of charged and neutral produced? Most of our results will depend on the quantities f_+ and f_0: the fractions of $\Upsilon(4S)$ decays to charged and neutral B mesons.

The reason for the dependence is simple. Suppose, for example, we reconstruct N charged B events in a particular decay mode with efficiency ϵ. The measured branching ratio to that mode is $N/\epsilon N_+$ where N_+ is the total number of charged B's produced. So, $N_+ = f_+ N_{\Upsilon(4S)} = f_+ \int Ldt \sigma_{\Upsilon(4S)}$ where $\int Ldt$ is the integrated luminosity and $\sigma_{\Upsilon(4S)}$ is the $\Upsilon(4S)$ cross section. Clearly, our measured branching ratio depends on f_+! We will assume f_+/f_0 is 1, and I will give you some justification for that when we discuss the masses of the charged and neutral mesons.

Another problem we will constantly be struggling with is that for all our measurements, whether from inclusive or exclusive processes, we must worry about contributions from the continuum: the background under the $\Upsilon(4S)$ resonance of $q\bar{q} \to u\bar{u}, d\bar{d}, c\bar{c}, s\bar{s}$ events. Both ARGUS and CLEO take a substantial amount of data (30% of the integrated luminosity in the case of CLEO) on the continuum 60-100 MeV below the $\Upsilon(4S)$ resonance. This is below $B\bar{B}$ threshold and this continuum data sample, properly scaled for the difference in luminosity and energy, can be used to subtract off continuum contributions to B meson signals at $\Upsilon(4S)$ energies.

Implicit in what I have just said is we are assuming that $\Upsilon(4S) \to B\bar{B}$ 100% of the time. This is almost certainly not the case. We know that ψ'' decays to non-$D\bar{D}$ final states,[11] and $\phi \to$ non-$K\bar{K}$ final states. The relevant question is what is the fraction of non-$B\bar{B}$ decays of the $\Upsilon(4S)$? We don't know the answer, but we can put a limit on it.

Consider the momentum spectrum of tracks from $\Upsilon(4S) \to B\bar{B} \to X$. The maximum momentum of any track is just half the mass of the B meson. However, in a direct decay, $\Upsilon(4S) \to X$, one can in principle get out tracks with half the CM energy. We can look at the inclusive momentum spectrum of all tracks from data taken at the $\Upsilon(4S)$ energy, shown in Fig. 4, and once we scale the continuum spectrum for the difference in luminosity and subtract it using our below resonance data, we see that $\Upsilon(4S)$ decays do not produce tracks with momentum higher than $M_B c/2$, half the B mass. Of course, to get a limit on non-$B\bar{B}$ decays out of this requires some assumptions about how the $\Upsilon(4S)$ decays to non-$B\bar{B}$ final states. If non-$B\bar{B}$ decays are like continuum events below $B\bar{B}$ threshold then $q = \sigma(\Upsilon(4S) \to nonB\bar{B})/\sigma(\Upsilon(4S) \to B\bar{B}) < 3.8\%$. On the other hand if the non-$B\bar{B}$ decays are like three-gluon decays of the $\Upsilon(1S)$, $q < 13\%$, both at 90% confidence level.[12]

The fraction of non-$B\bar{B}$ decays of the $\Upsilon(4S)$ is small but we think we know it

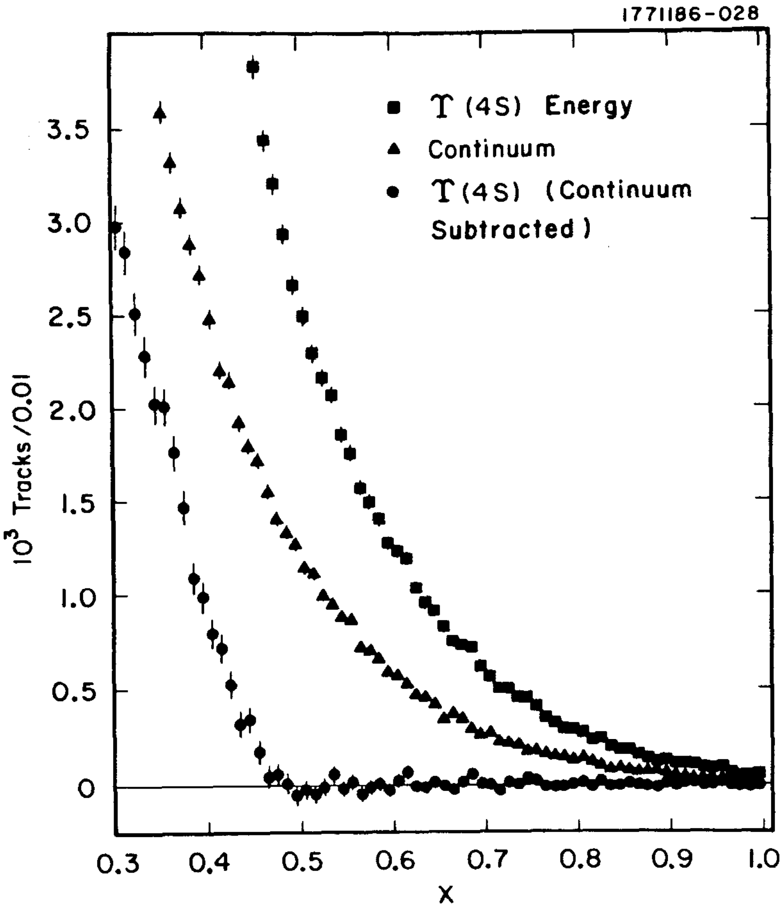

Figure 4. The inclusive charged particle momentum distribution from CLEO at the $\Upsilon(4S)$, on the continuum and the $\Upsilon(4S)$ distribution after subtracting the continuum contribution, scaled for the difference in luminosity and energy. The horizontal scale, x, is the particle momentum divided by the beam energy.

is not zero. Both CLEO[13] and ARGUS[14] report seeing ψ mesons produced from $\Upsilon(4S)$ decays which are too energetic to originate from B decay. The spectrum of ψ's from the $\Upsilon(4S)$ at CLEO is shown in Fig. 5. The kinematic limit for a ψ coming from the decay of a B meson is indicated and clearly there are events past that limit. Because we don't know what else to do, we will assume that $\Upsilon(4S) \to B\bar{B}$ 100% of the time and that $f_+/f_0 = 1$. But keep in mind there is uncertainty in those numbers.

B. Decays of B Mesons

We are now ready to discuss how B mesons decay. In order to decay, the b quark in the B meson must change its flavor, and this can only happen in a weak decay. According to the GIM mechanism[15] the neutral weak currents (Z^0 emission) conserve flavor, and it is only by $W^\pm$ emission that quarks can change their flavor. The most simple minded picture of $\bar{B}^0$ decay is shown in Fig. 6a. If we ignore the light quark (this is the "spectator model") then the decay of a B meson looks like muon decay. There are, of course, a few additional subtleties: we need to include a factor of V_{cb} at the W vertex since mesons are made of quarks of definite flavor, but the weak eigenstates are not flavor eigenstates so we need the appropriate CKM matrix element to convert between them. There will be form factors that describe how to turn free quarks into hadrons, and the decay rate will also depend on the available phase space.

There are two spectator diagrams for both charged and neutral B's shown in Fig. 6a., one where the b quark turns into a c quark and the other where a b quark turns into a u quark. As we shall see later, $V_{ub} << V_{cb}$, and b decays to charm dominate. We will discuss the measurements of V_{ub} and V_{cb} at length when we discuss semi-leptonic decays of the B. We should just note that V_{tb} is the dominant CKM matrix element involving b quarks, and given a chance, a b quark would preferentially decay to top. Of course, it is not given that choice. A $b \to t$ decay is kinematically forbidden which helps keep the B lifetime long!

We can make a very simple prediction for the semi-leptonic branching fraction of the B meson based on this quark level diagram. If we assume that $b \to c$ transitions dominate, then the total decay rate is just the sum of the partial rates for the W to decay to $\bar{u}d$, $\bar{c}s$, $e^-\bar{\nu}_e$, $\mu^-\bar{\nu}_\mu$, and $\tau^-\bar{\nu}_\tau$. For the quark decay modes we must allow for the 3 possible color states, and we must take into account the smaller phase space for the charm and tau decay modes. We find

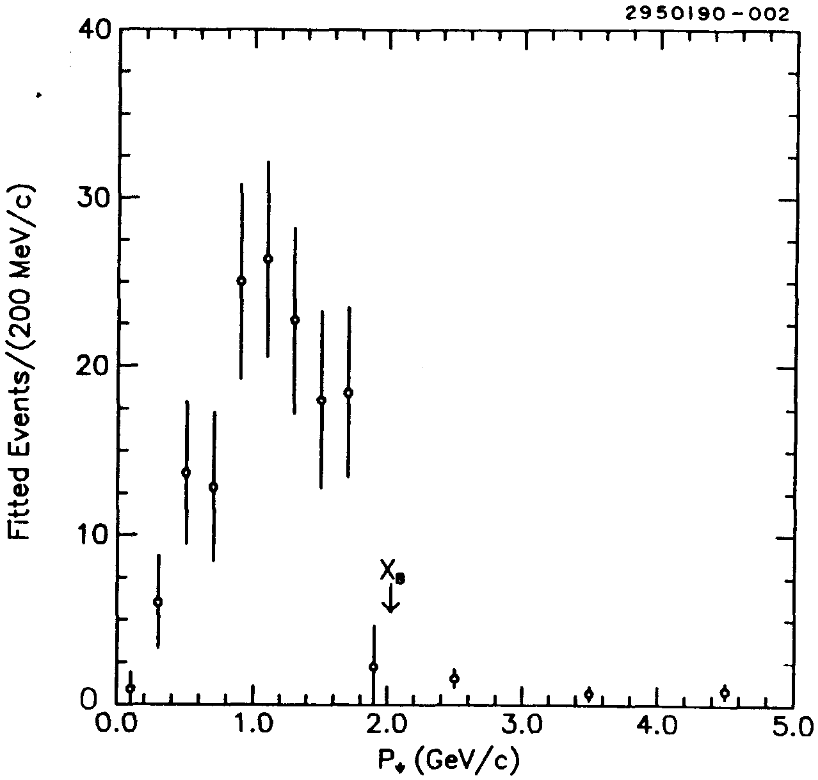

Figure 5. The CLEO momentum distribution for ψ's from $\Upsilon(4S)$ decays. The maximum ψ momentum from a two body B decay is indicated by X_B.

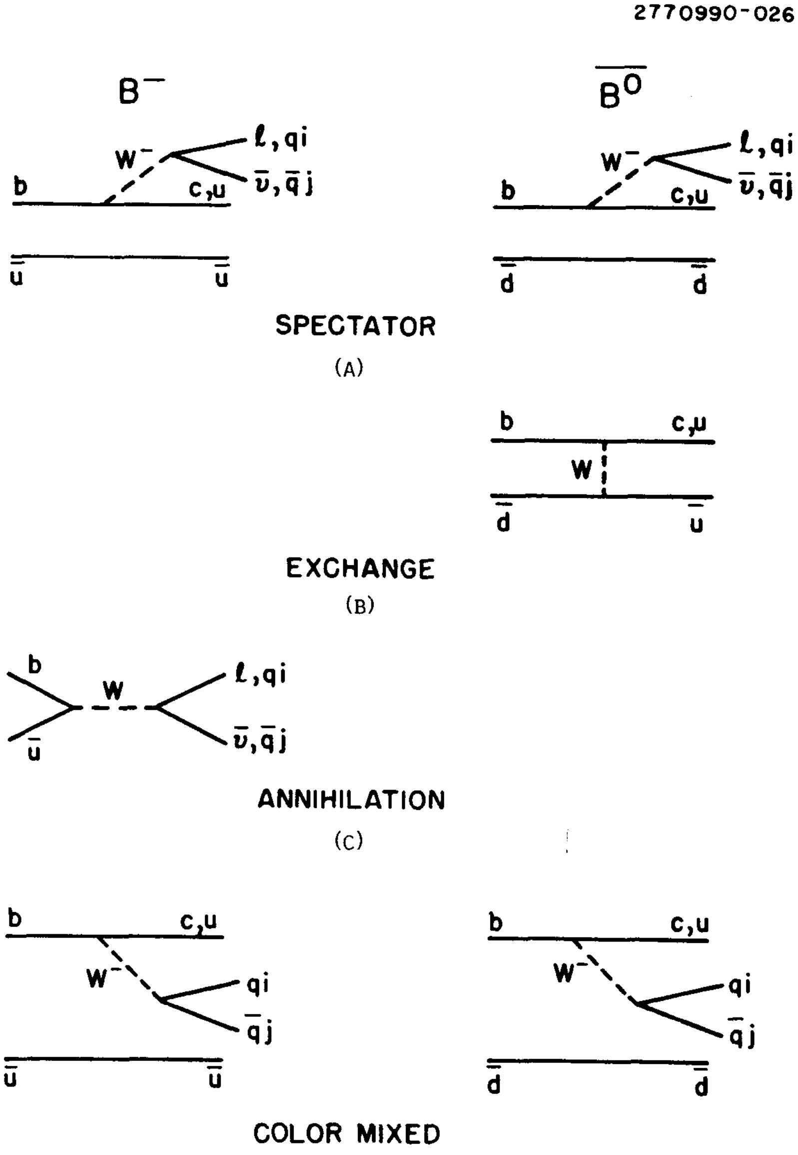

Figure 6. Lowest order Feynman diagrams for B decay.

Decay Mode	Color Factor	Phase space	Relative Rate
$W^- \rightarrow \bar{u}d$	3	.48	1.5
$W^- \rightarrow \bar{c}s$	3	.15	.45
$W^- \rightarrow e^-\bar{\nu}_e$	1	.48	.5
$W^- \rightarrow \mu^-\bar{\nu}_\mu$	1	.48	.5
$W^- \rightarrow \tau^-\bar{\nu}_\tau$	1	.15	.15
Total			3.1

From this we can calculate that $Br(B \rightarrow e\bar{\nu}_e x_c) \simeq Br(B \rightarrow \mu\bar{\nu}_\mu x_c) = \frac{.5}{3.1} = 16\%$ which is large! Naively we predict almost 30% of B decays to electrons and muons in the final state. If we include QCD corrections to hadronic final states (gluon radiation) this decreases the leptonic branching ratio to about 13%. The measured semi-leptonic branching ratio for B's is 10.4% for each electron and muon. The difference between the measured value of 10.4% and the theoretical expectation of 13% is not understood, although there is speculation that non-$B\bar{B}$ decays of the $\Upsilon(4S)$ could account for it.[16]

In the simple spectator model of B decays presented so far, we treat charged and neutral B's identically, since they differ only in the flavor of the light quark, and we are ignoring the possible influence of the light quark. We would predict, based on this model, that the lifetime of the charged and neutral B are identical. If we allow ourselves to be a bit more sophisticated, we quickly see that this is not necessarily the case.

If we look at all the possible first order diagrams describing B decay in Fig. 6a-d, we see that the spectator diagram is the dominant way for the B^- to decay, but that the $\bar{B}^0$ can decay both via a spectator process, and a W exchange. (There is an annihilation contribution to the B^- decay, but that is supressed by the vertex factor V_{ub}.) What is the importance of the exchange contribution to the $\bar{B}^0$ lifetime? If we look at the D mesons, for which one can draw an entirely analogous set of decay diagrams, we might be tempted to conclude that as go the D's, so go the B's. Since we know there is a large difference in the charged and neutral D lifetime ($\tau_+/\tau_0 \sim 2.4$)[17] due in part to the contribution from the exchange diagram and possibly also due to interference with color mixed diagrams, we should perhaps expect that the B^- lifetime will be larger than $\bar{B}^0$. In fact, because the b quark is so much heavier than the light quarks, it is thought that the non-spectator diagrams will be less important in B decay than D decay and the charged to neutral lifetime ratio will be closer to one. At the moment, it is an open experimental question.

We can summarize some useful general features of B meson decay, which will serve as a guide on how to do experiments with B mesons.

(1) The branching ratio to leptons is large. Our naive calculation gave 30% of B decays are to electrons and muons. In fact the measured branching ratio is: $Br(B \rightarrow Xe\bar{\nu}) = Br(B \rightarrow Y\mu\bar{\nu}) = 10.4\%$.

(2) The branching ratio to any exclusive mode is small.[17] The largest measured branching ratios are for modes like $B^- \rightarrow D^{*+}\pi^-\pi^-\pi^0$ or $\bar{B}^0 \rightarrow D^{*+}\pi^-\pi^-\pi^+\pi^0$ with branching ratios of 2-4%. Typical branching ratios to a given exclusive mode are less than 1%. Given the large Q of the B decay of almost 3.5 GeV, the large multiplicity of decay modes is not surprising.

(3) The average $\Upsilon(4S)$ decay into a pair of B mesons has 11 charged particles and 10 photons in the final state.[18] The combinatoric backgrounds to reconstruction are substantial since the decay products of the 2 B's overlap, and good neutral and charged particle information is crucial to do physics.

(4) By looking at the inclusive momentum spectrum for decays such as $B \rightarrow D^{*+}x$, D^0x, D^+x, we can see how often the charmed mesons are produced in a two-body decay. In a two-body decay $B \rightarrow Dx$, the D will come off roughly monochromatically. Figure 7 shows the inclusive D spectrum vs x where $x = p_0/p_{max}$,[19] and in fact the spectrum is rather broad, indicating a predominance of multi-body decays.

C. The Spin of the B Meson

We would expect that B mesons produced at the $\Upsilon(4S)$ are spin 0 rather than spin 1 since the observed pseudoscalar states are lighter than vector states (i.e., $D^* - D$, $K^* - K$ etc.). The way the spin of the B can be determined is by looking at the production angle of the B's relative to the beam line. This is done using B's which are fully reconstructed (so $\vec{p}_B$ is known) using techniques I'll describe in a minute.

The $\Upsilon(4S)$ has the quantum numbers of the virtual photon and is in a $J = 1$, $J_Z = \pm 1$ state. If the $\Upsilon(4S)$ decays to a pair of spin 0 particles, then angular momentum must go somewhere so the 2 B mesons come off in a relative P state with a $sin^2\theta$ angular distribution[20] (θ is the angle to the beam axis). Figure 8 shows the polar angular distribution of reconstructed B's indicating a $sin^2\theta$ distribution.[21]

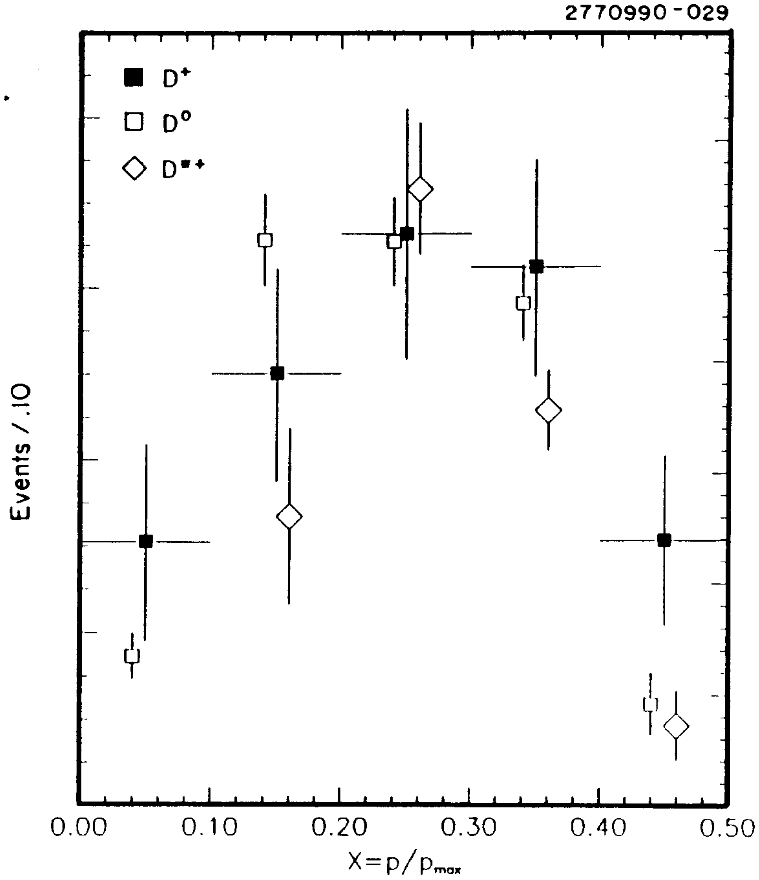

Figure 7. Inclusive momentum spectra from CLEO for D's produced in B decay; $x = p/p_{max}$.

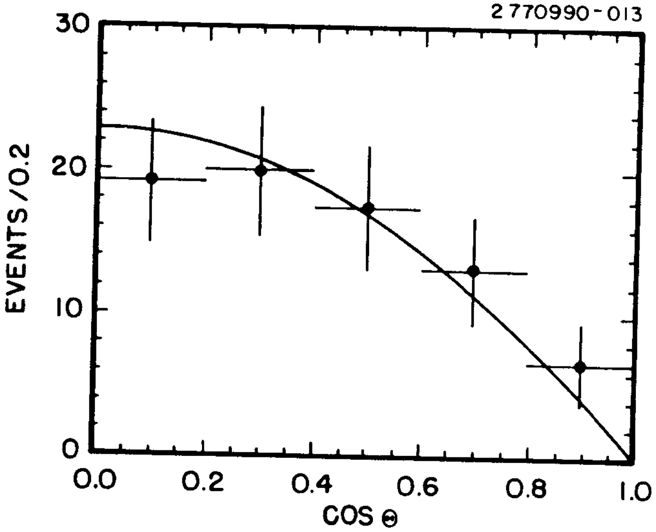

Figure 8. The distribution of reconstructed B's in polar angle from ARGUS.

D. The Masses of the B Mesons

The masses of the light B mesons are measured by CLEO and ARGUS using the same techniques: exclusive reconstruction. The basic idea is to fully reconstruct a B meson from its decay products. All the decay modes that ARGUS and CLEO fully reconstruct have either a charmed particle (D^0, D^+, D^{*+}, D^{*0}) or a particle with hidden charm (J/ψ) in the final state, thereby taking advantage of the dominant decay chain $b \rightarrow c$.

Figure 9 shows the mass distribution for $K^-\pi^+$ combinations for hadronic events from the $\Upsilon(4S)$ and from the continuum.[19] Since the D^0 coming from a B can have an energy of at most half the B energy, the energy of the D candidates has been restricted to be less than half the beam energy which is the kinematic limit for a 2 body B decay. We see a signal on top of a substantial combinatoric background from continuum. (The histogram is obtained from data taken below the $\Upsilon(4S)$ resonance.) To form a B, the heavy meson candidate (such as the D^0) will be required to be within 2σ of its known mass. It will then be combined with other tracks in the event to form a B candidate,i.e., $D^0\pi^+$.

We can take advantage of the topology of events to reduce background in the reconstruction process. Because the B has spin 0, the angle between the B direction and the beam axis is proportional to $sin^2\theta$. The continuum events are isotropic so we can reject 20% of the continuum background with a cut $|cos\theta_B| > 0.8$, and only lose 5% of the signal. The event shape can also be used to supress continuum. Continuum background events are supressed by exploiting the fact that the spatial distribution of the decay products of the 2 B's are uncorrelated, while continuum events are jet-like. Finally, the energy difference between the measured energy of the B candidate and the beam energy (the true B energy) must be within 2σ of 0. This is to exclude genuine B decay candidates where an additional particle has been missed in the analysis, and it is also sensitive enough to reject candidates with tracks that have been given the wrong mass assignments.

For particle combinations that pass all of these cuts, we can now compute a mass for the B meson candidate. The obvious thing to do is to compute

$$M_B^2 = [\sum E_i]^2 - [\sum \vec{p}_i]^2,$$

where the subscript i refers to the tracks making up the candidate B meson. We can rewrite the above expression as

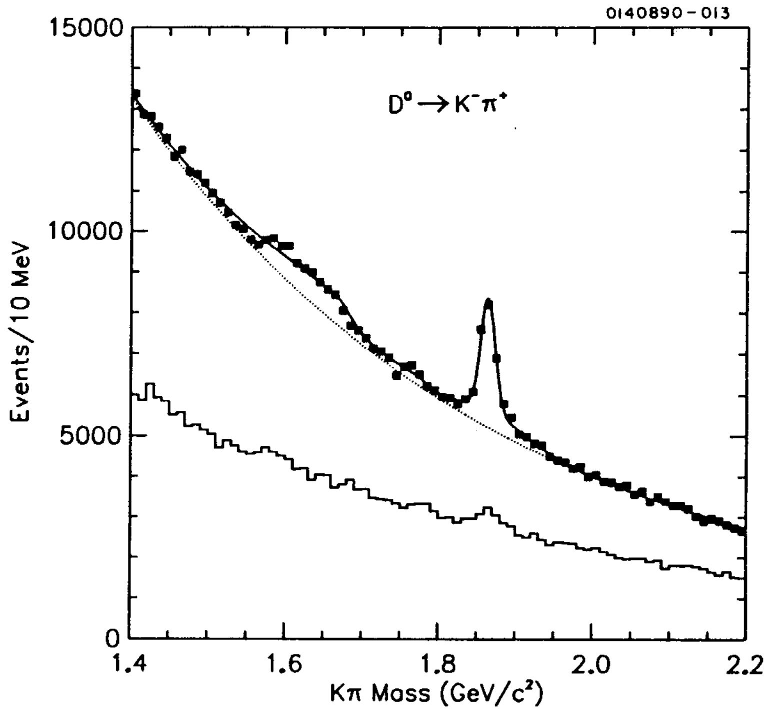

Figure 9. $K^-\pi^+$ mass distribution from CLEO for data taken at the $\Upsilon(4S)$ (dots) and continuum (histogram) showing D^0 signal.

$$M_B^2 = [\sum_i \sqrt{p_i^2 + M_i^2}]^2 - [\sum \vec{p}_i]^2$$

where, again, the sum over i is the sum over the tracks making up a candidate B meson. This expression gives a mass resolution of about 20 MeV. The uncertainty in M_B^2 dominated by the uncertainty in the measurement of p_i from the first term. The uncertainty in the 2nd term in this expression is much smaller because $[\sum \vec{p}_i]^2$ is a small number. It is just the momentum of the B meson which we know is tiny (317 MeV). But $[\sum E_i]^2$ is just the energy of the B meson and we know what that is: it is just the beam energy. So we can write

$$M_B^2 = E_{Beam}^2 - [\sum \vec{p}_i]^2$$

where E_{Beam} is the energy of the electron and positron beam. The beam energy resolution is dominated by synchrotron radiation and is approximately 2 MeV at CESR and 4 MeV at DORIS. The net resolution on the B mass is 2.6 MeV, a factor of 10 better! This technique is called "beam constrained mass" and of course, it only works since $\Upsilon(4S) \to B\bar{B}$ and nothing else.

Figure 10 shows the B mass distributions for charged and neutral B mesons from CLEO[22] and ARGUS.[21]Only clean modes, with no neutrals are used in the mass determination since they have low background. CLEO fits their signal with a Gaussian signal and flat background. ARGUS uses a rather different background shape. The results of the fit are

Table II
Measured B Meson Masses

	ARGUS	CLEO
M_{B^0} (MeV)	$5,279.6 \pm 0.7 \pm 2.0$	$5,278.0 \pm 0.4 \pm 2.0$
M_{B^+} (MeV)	$5,280.5 \pm 1.0 \pm 2.0$	$5,278.3 \pm 0.4 \pm 2.0$
$\Delta M = M_{B^0} - M_{B^+}$ (MeV)	$-0.9 \pm 1.2 \pm 0.5$	$-0.4 \pm 0.6 \pm 0.5$

The mass difference is a particularly interesting number since it is related to f_0/f_+, the ratio of neutral to charged mesons produced at the $\Upsilon(4S)$. An interesting observation is that if you had been asked what you expected the mass difference to be, you might have gone to the particle data book[17]and noticed the following:

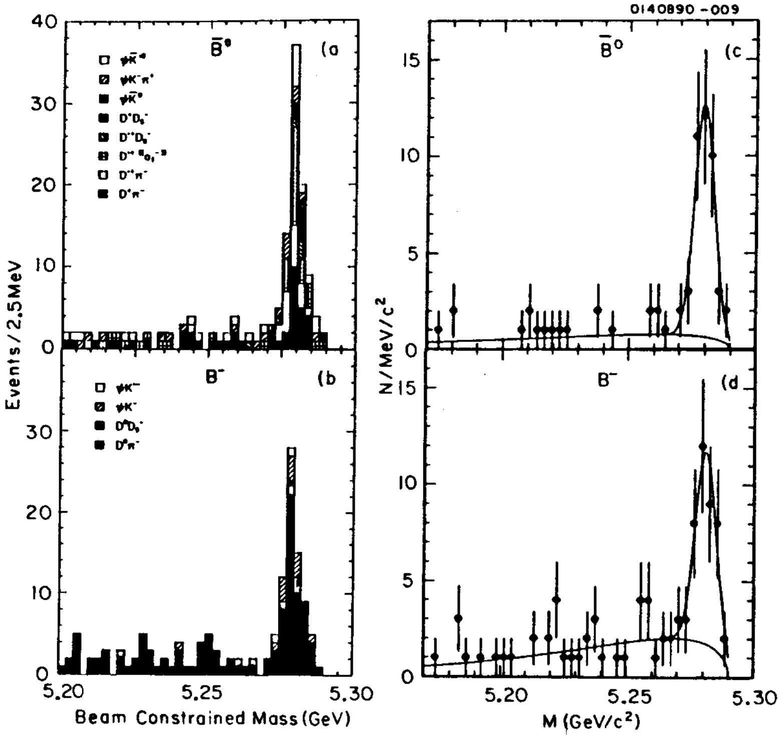

Figure 10. Mass distributions of charged and neutral B meson candidates from (a)(b) CLEO and (c)(d) ARGUS that are used in the determination of the B meson masses.

$$M_{\pi^+} - M_{\pi^0} = 4.59\ MeV$$
$$M_{K^+} - M_{K^0} = -4.02\ MeV$$
$$M_{D^+} - M_{D^0} = 4.74\ MeV.$$

Clearly there should be a mass difference between the charged and neutral B mesons of a few MeV, with the neutral meson being slightly heavier due to the splitting of the up and down quark masses. Neither ARGUS nor CLEO confirms this and it is a puzzle.

I said earlier that a mass difference between the neutral and charged mesons would affect the production ratio, f_0/f_+. If the two mesons have equal masses, then the phase space for $\Upsilon(4S) \rightarrow B^+B^-$ or $\Upsilon(4S) \rightarrow B^0\bar{B}^0$ is identical so you might conclude that the charged and neutral mesons are produced in equal abundance. That assumption is a bit naive because it neglects coulomb interactions between the final state mesons. The charged mesons attract each other, enhancing the value of the meson wave functions at the origin, and that can enhance production by as much as 18%[23] if the B mesons were point like particles. Peter Lepage has recently done a calculation pointing out that this too is naive.[24] The structure of the mesons cannot be ignored and he finds somewhere between a 3% supression and a 4% enhancement of charged B production near threshold. For the moment, we will use $f_+/f_0 = 1$ based on ΔM being very close to zero and Peter's calculation which says the coulomb corrections don't give big surprises. In the future, a sample of double tagged events: events where we can reconstruct both B's in the event, will allow us to actually measure f_+/f_0.

E. B Meson Lifetime

The measurement of the B meson lifetime is important for two reasons. It is a fundamental parameter of the meson, and it can be combined with a measurement of the semi-leptonic branching ratio to determine V_{cb}, the CKM matrix element.

The B lifetime is measured at PEP and PETRA energies where the meson is produced with a sufficient boost to travel a measurable distance before it decays. The difficulty faced in this experiment is that $b\bar{b}$ events are only ~ 10% of the total hadronic event sample. The b sample must be enhanced before the lifetime can be measured. There is a very nice review by Rene Ong[25] which summarizes the techniques commonly used in making a B lifetime measurement. I will concentrate on a single method.

The B meson decays to a lepton roughly 20% of the time. Leptons from B decay have higher transverse momentum relative to the parent B direction than leptons from charm or light quark decays due to the high mass of the b quark. By requiring events with leptons that have a p_t of greater than 1 GeV/c with respect to the thrust axis of the event, which is taken as the estimator of the parent B direction, the Mark II at PEP was able to obtain a B fraction of $(65 \pm 5)\%$ in their event sample.[25] Once a B enriched data sample is obtained, the lifetime of the B meson is measured by determining either the displacement of the average vertex of the event from the beam centroid, or the impact parameter of the high p_t lepton with respect to the estimated production point of the B, which is either the beam centroid, or determined by other tracks in the event.

The lifetime measured with these techniques is the "average" lifetime of a combination of charged and neutral B's, as well as B_s and Λ_b. The world average "average" B lifetime is now determined to be

$$1.18 \pm 0.14\ psec.$$ [17]

It will turn out to be very important for the determination of the CKM matrix element V_{cb} to have the exclusive B^+ or B^0 lifetime. There are two ways to get at the exclusive charged and neutral B lifetimes: one uses the semi-leptonic decay rate and I will discuss it in detail in subsequent chapters. The other is to directly measure the B^0 lifetime as has recently been done by the Mark II using PEP data.

The technique the Mark II uses is a bold one.[26] They partially reconstruct $\bar{B}^0 \rightarrow D^{*+}\ell^-\bar{\nu}$ with $D^{*+} \rightarrow D^0\pi^+$, but they do not reconstruct the D^0 since the loss of efficiency would be prohibitive. They form D^0 candidates by adding all charged tracks in the leptons thrust hemisphere with $p_{||} > 0.5$ GeV/c except the lepton and a candidate bachelor pion (from $D^{*+} \rightarrow D^0\pi^+$) and all photons with $p_{||} > 1.0$ GeV/c where $p_{||}$ refers to the momentum parallel to the thrust axis. Quite impressively when combining the D^0 candidates with the bachelor π they see a peak in the $D^* - D^0$ mass difference when the pion and lepton have the opposite sign (signal) but no peak when they have the same sign (background), as shown in Fig. 11. After track quality cuts they end up with a sample of 15 $D^{*-}\ell^+$ pairs from which they can determine the lifetime of the parent particle by calculating the vertex of all tracks and measuring its displacement from beam center. They measure a B^0 lifetime of

$$\tau_{B_0} = 1.20 \pm 0.36 \pm 0.14\ \ psec$$

which indicates, when compared with the average B lifetime of 1.18 psec, that the charged and neutral B's have similar lifetimes, although errors are still large.

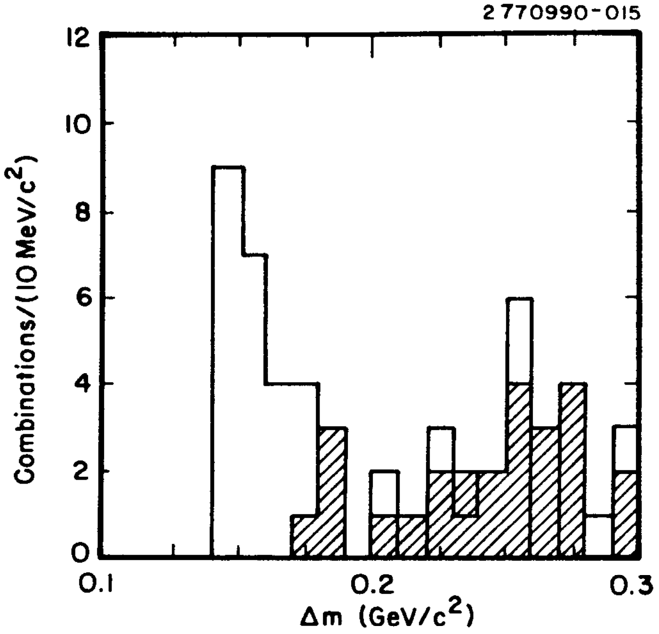

Figure 11. The $D^{*+} - D^0$ mass difference distribution from the MARK II for all D^0-candidate-bachelor-pion combinations. The solid line indicates combinations where the high p_t lepton and the bachelor pion have opposite sign, and the hatched area is for same sign combinations.

3. Semi-Leptonic B Decays

I now want to concentrate on semi-leptonic decays of the B meson. They are of particular importance in the study of B decay, and it is straight forward to understand why. In a semi-leptonic decay of the B meson, the b quark in the meson decays to a charm or up quark with the emission of a W^- boson, which then decays into a lepton and an antineutrino, as shown in Fig. 12. There can be no question of the light quark participating in the decay, and so the diagram is pure spectator. The leptonic decay of the W is well understood. The coupling at the W vertex is V-A with a coupling constant given by the standard model. This is separated from the hadronic vertex which one assumes is V-A and contains a CKM matrix element V_{cb} or V_{ub} to describe the coupling of different quark flavors. The effects of the strong interactions are contained in the form factors which describe the formation of the final state meson. Relatively speaking, the semi-leptonic decay gives us a "clean" probe of the quark decay.

As we noted last lecture, the branching ratio to leptons is large in B decay: $Br(B \to X\ell\nu) = 10.4\%$. Furthermore, leptons are relatively easy to detect, especially at higher momenta. Muons are most often detected by their ability to penetrate magnet iron to an outer detector, and electrons can be uniquely identified in electromagnetic calorimeters. The usefulness of leptons as a probe of B decays is the result of a combination, then, of their experimental accessibility and their theoretical simplicity.

Many experiments have taken advantage of leptons to identify b quark events in their data. This is because a lepton in a hadronic event is a signature of a weak decay and the heavy b quark must undergo a weak decay to change its flavor. Of course there are other sources of leptons in hadronic events besides B's. For example, the semileptonic branching ratio for a charged D meson is almost 20%, but from bottom and lighter charm or strange quark decays can be separated by total lepton momentum or the component of the momentum transverse to the event axis.

PEP and PETRA experiments typically require a lepton with high transverse momentum ($p_t > 1\text{GeV/c}$) with respect to the thrust axis of a hadronic event to enrich their B sample. The lepton signals a weak decay and the p_t requirement enhances b over c and s due to the much larger mass of the b quark. Similarly CDF and UA1 use leptons to identify B events. There the problem is somewhat reversed. Those experiments are not designed to trigger on low p_t leptons (after all, their primary concern was the high p_t physics of W, Z and top production) so the trigger alone biases them very heavily towards b events rather than charm. In fact, the challenge CDF now has is to lower their minimum p_t cut on muons

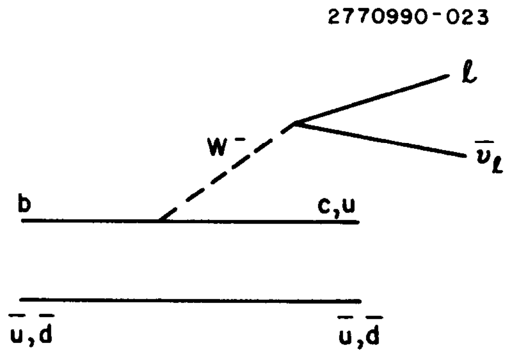

Figure 12. First order Feynman diagrams for semi-leptonic B meson decay.

to accept more B events and still have an acceptably low trigger rate. Despite these difficulties, CDF is demonstrating they can do B physics even with $S/B = 1/1000$. In addition to the reconstruction of ψK^-, they have seen D^0's in jets with leptons that are consistent with coming from B decay.

Figure 13 shows $K^+\pi^-$ combinations in jets with e^+ (or charge conjugate combination)[27] This is the correct combination of signs to come from B decay and we see a nice $\bar{D}^0$ peak. How do we know these D's are from B's? When CDF looks at $K^+\pi^-$ combinations in jets with e^- (a sign combination incompatible with coming from a B), they don't see a $\bar{D}^0$ signal.

At the $\Upsilon(4S)$, requiring a lepton supresses the continuum background under the $\Upsilon(4S)$. This is even more powerful if a minimum momentum cut of around 1 GeV is applied to the lepton. Figure 14(a) shows the inclusive spectrum of leptons from the continuum at CLEO which is clearly peaked at low momentum. The inclusive lepton spectrum from the $\Upsilon(4S)$ is shown in Fig. 14(b) (where the background from the continuum under the 4S has already been subtracted). Above 1 GeV, leptons from B decays dominate the spectrum. Below that momentum there is considerable contamination from cascade decays where $b \to c$ and then the charm quark decays semileptonically. It is clear the requirement of a $> 1\mathrm{GeV/c}$ lepton in $\Upsilon(4S)$ events will greatly enhance the "b-ness" of our sample.

I am going to concentrate on the extraction of the elements of the quark mixing matrix: $|V_{cb}|$, $|V_{ub}|$, $|V_{td}|$, using semileptonic B decays. I want to emphasize that the methods I will describe are crude, and that this procedure of extracting CKM matrix elements will become much more rigorous and exact in the coming years. I will try to give you some indications on how we will be improving this. I will start with a discussion of measurements of the semi-leptonic decay rate, and its relation to the B lifetime and the extraction of V_{cb}. I will also discuss progress towards the determination of the exclusive lifetimes of B^- and $\bar{B}^0$. Then I will discuss the limits on V_{ub} from the lepton endpoint spectrum, and I will end with a discussion of $B^0\bar{B}^0$ mixing.

A. Inclusive Semi-Leptonic Decays and V_{cb}

We have two basic probes of the semi-leptonic decay rate: we can measure the inclusive momentum spectrum of the emitted lepton, or we can measure the decay rate into a few exclusive channels such as $B \to D\ell\bar{\nu}$ or $B \to D^*\ell\bar{\nu}$. We will start with the inclusive spectrum. The CLEO inclusive electron spectrum from $\Upsilon(4S)$ decays is shown in Figure 14(b). Recall this spectrum is generated by taking the inclusive lepton spectrum at the $\Upsilon(4S)$ energy for leptons in hadronic events, subtracting fakes and correcting for detector efficiency, and then doing a bin by bin subtraction of the continuum lepton spectrum (similarly corrected)

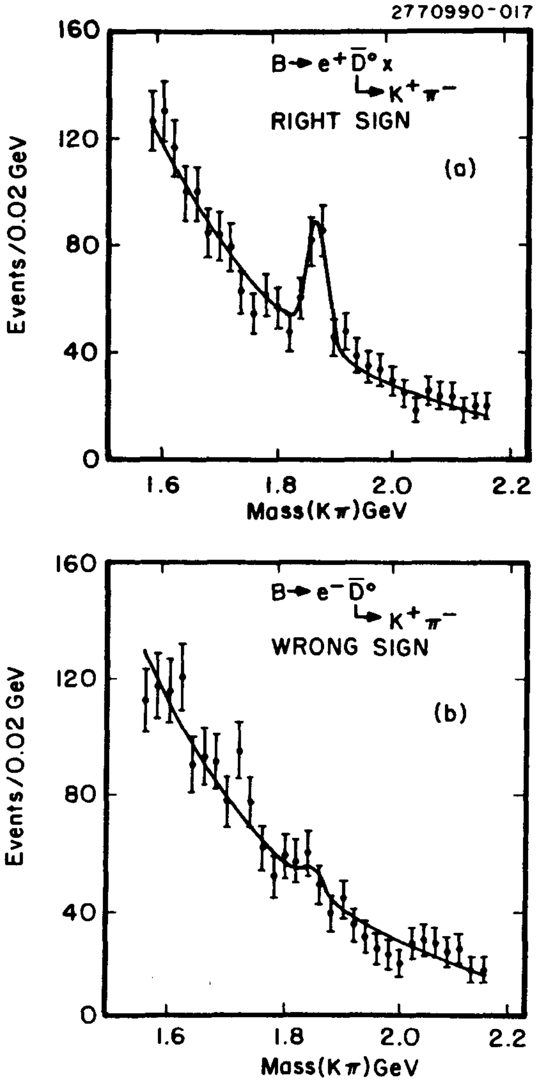

Figure 13. CDF data showing the invariant mass of two track combinations ($K^+\pi^-$) in jets with electrons: (a) when the K^+ and the electron have the same sign (b) when the K^+ and electron have opposite sign.

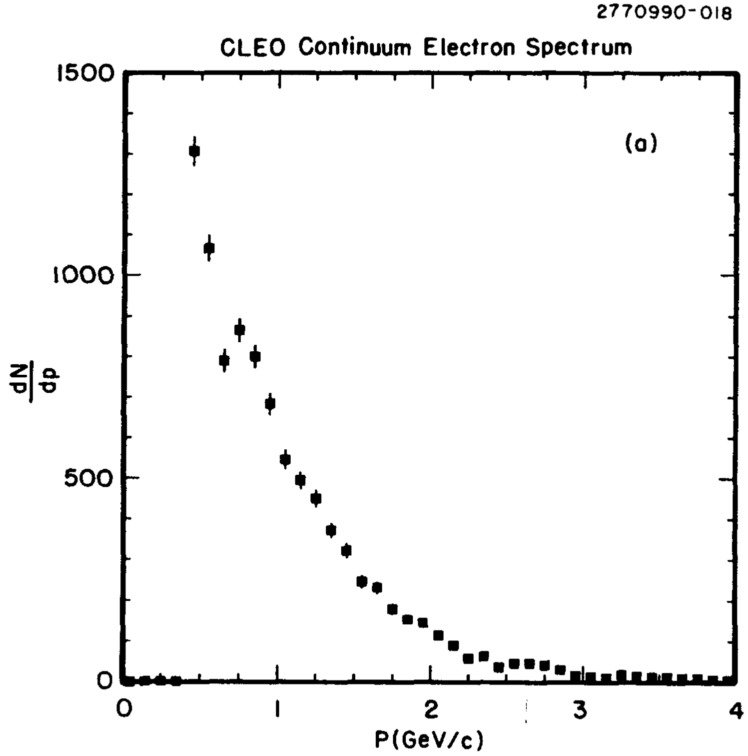

Figure 14*a*. The CLEO inclusive electron momentum spectrum from continuum.

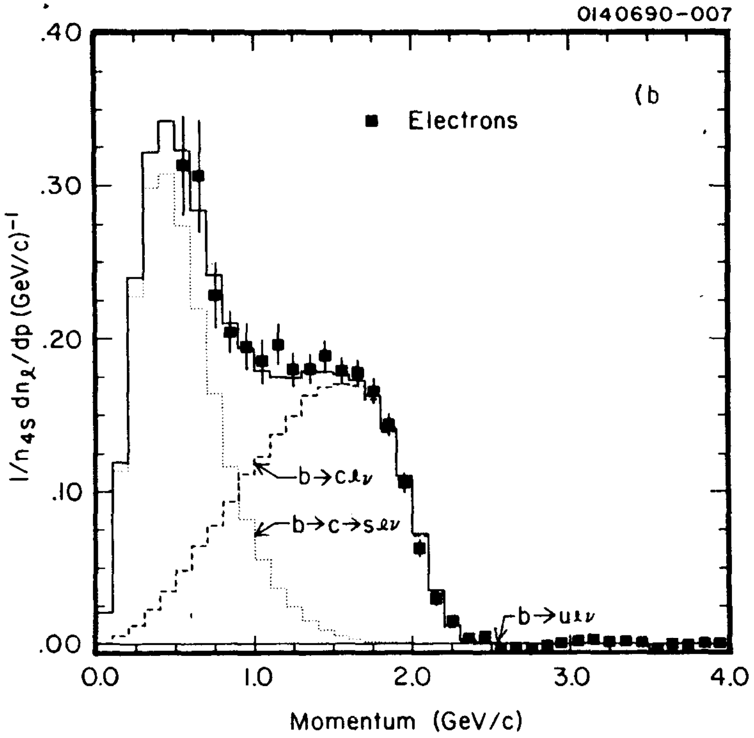

*Figure*14*b*. The CLEO inclusive electron spectrum from $\Upsilon(4S)$ decays.

from data taken below the $\Upsilon(4S)$. In this way, contributions to the spectrum from leptons that do not originate from $\Upsilon(4S)$ decays are removed. If we assume that $\Upsilon(4S) \to B\bar{B}$ 100% of the time, then this spectrum is the inclusive lepton spectrum from B-decays. There are two dominant components to the lepton spectrum. (I should note that contributions from $B \to \psi X$, $\psi \to \ell^+\ell$ and $B \to \tau x$, $\tau \to \nu_\tau \ell \bar{\nu}_\ell$ have been subtracted.) The spectrum contains leptons from direct semi-leptonic decays of the b quark: $b \to c\ell\bar{\nu}$ and $b \to u\ell\bar{\nu}$. These are called primary leptons. The spectrum also contains leptons from cascade decays $b \to c \to s\ell\nu$ where the B meson decays to a D, and the D decays semi-leptonically. These secondary leptons have a softer spectrum and dominate at low momentum.

In order to extract an average semi-leptonic decay rate (average since it is averaged over both charged and neutral B's), we need to fit the spectrum, and in order to do that, we have to use a theoretical model.

Until now, we have had to rely on a variety of phenomenological models which fall into 2 basic categories. The simplest models of semi-leptonic B decay are the free quark models.[28][29] The heavy quark is treated as free and is allowed to decay in analogy with muon decay. These models essentially start at the quark level and predict the full inclusive lepton momentum spectrum. They say nothing about branching ratios to exclusive states such as $D^*\ell\bar{\nu}$ or $D\ell\bar{\nu}$. The second class of models is called exclusive or bound state models. They calculate a set of exclusive channels which is postulated to saturate the total rate. There are several of these models.[30][31][32] The significant differences between them are all in how the hadronic form factors are calculated. At the risk of insulting the theorists, it appears that the form factor models to date all involve various degrees of educated guesses. What is quite amazing is that for decays $B \to X_c\ell\nu$ with a charmed quark in the final state, the models agree quite well. These models clearly do give branching ratios to exclusive final states.

There are two new models on the market. One is a hybrid formed from the models just described.[33] It uses the bound state models at low hadronic recoil energy where bound states should dominate and matches on to the quark model calculations at high recoil where they are most accurate. The basic idea is to give the full Dalitz plot equal weight.

The second new method[8] is, apparently, the wave of the future. Here QCD can be used to derive a rigorous relation between the form factors in D decay and B decay as opposed to previous models which simply guessed at the form factors.[34] The form factors in D decay are being measured by E691 in decays such as $D^+ \to \bar{K}^{*0}e^+\nu_e$. The goal is to use these form factors in B decay and thereby reduce the uncertainty in the extraction of V_{ub} and V_{cb}.

After this digression, let's get back to the experimental problem at hand which is the extraction of the semi-leptonic branching ratio and V_{cb} from the inclusive lepton spectrum. Both CLEO and ARGUS determine the semi-leptonic branching ratio by fitting the observed inclusive spectrum to theoretical models. ARGUS fits the experimental spectrum above 1.4 GeV/c where the contribution from cascade decays is small and uses models to extrapolate to the full spectrum. CLEO fits the full spectrum to a sum of the primary and secondary spectra. The secondary spectrum is obtained by folding the measured lepton spectrum from semi-leptonic D decays with the measured momentum spectrum for D mesons produced in B decay. The results for the average semi-leptonic branching ratio from CLEO and ARGUS are given in Table 3 where the free quark model of Altarelli et al. (ACCMM),[28] and the form factor model of Grinstein et al. (ISGW),[30] have been used to extrapolate the spectrum.

Table 3.
Inclusive B meson semi-leptonic branching ratios and values for V_{cb}.

Model	ACCMM Branching ratio %	ISGW Branching Ratio %	ACCMM $\lvert V_{cb}\rvert$	ISGW $\lvert V_{cb}\rvert$
CLEO	$10.4 \pm 0.2 \pm 0.4$	$10.0 \pm 0.1 \pm 0.3$	$0.046 \pm .001 \pm .006$	$0.045 \pm .001 \pm .007$
ARGUS	$10.2 \pm 0.4 \pm 0.2$	9.8 ± 0.4	$0.046 \pm .002 \pm .006$	$0.045 \pm .001 \pm .007$

How do we now extract V_{cb}? If we look at the decay $b \to c\ell\nu$, it looks remarkably like the decay of a muon, and we can write down an expression for the rate

$$\Gamma(b \to c\ell\nu) = \frac{G_F^2 M_b^5}{192\pi^3} |V_{cb}|^2 f_{cb}(M_b, M_c)$$

where we have taken the familiar formula for muon decay and substituted in the mass of the b quark for the muon mass. The factor V_{cb} comes from the CKM matrix and $f_{cb}(M_b, M_c)$ describes the phase space for the final state relative to the phase space for muon decay and is approximately .49. I am ignoring V_{ub} in this expression and that will be justified later when you see how small V_{ub} is.

Experimentally, we measure the semi-leptonic branching ratio

$$Br(B \to X\ell\nu) = \frac{\Gamma(b \to X\ell\nu)}{\Gamma_{TOT}}.$$

Γ_{TOT} is related to the B lifetime so we have $1/\tau_b = \Gamma_{TOT}$ or

$$\frac{Br(B \to X\ell\nu)}{\tau_b} = \frac{G_F^2 M_b^5}{192\pi^3} |V_{cb}| * .49.$$

This formula is naive since it totally ignores the difference between a free quark and a meson. The models mentioned above give corrections due to the interaction with the spectator quark, and gluons in the final state. We can now plug in the measured B meson lifetime, the measured leptonic branching ratio, M_b, G_F and extract the values for $|V_{cb}|$ given in Table 3. The first error quoted in Table 3 gives the experimental statistical and systematic error added in quadrative. The second error includes the model uncertainties, the statistical and systematic uncertainty in the measured B lifetime, and an additional error of 20% in the lifetime that has been added to account for our uncertainty in the B^+ and B^0 lifetime relative to the B lifetime averaged over all B species. The constraints placed on V_{cb} using this method have some notable weaknesses. (1) There is uncertainty in what to use for M_b. (2) The phase space factor depends on both M_b, and on M_c, which is equally uncertain. (3) To date, the best lifetime measurements are average B lifetime measurements, meaning they are averaged over an unknown mixture of charged and neutral B's, B_s, Λ_b and so on, while the branching ratio is averaged over a mixture of B^- and $\bar{B}^0$. It is the uncertainty in these quantities that dominates the error on $|V_{cb}|$.

Given the weaknesses of this inclusive method, it is instructive to ask if we can improve our knowledge of V_{cb} by looking in exclusive semi-leptonic B decays. The answer is that we can't yet, but with more data, this is the right way to do it.

B. Exclusive Semi-leptonic Decays and V_{cb}

We want to use the relation $Br(\bar{B}^0 \to D^{*+}\ell^-\bar{\nu})/\tau(B^0) = \alpha|V_{cb}|^2$. There are several things we need to do: (1) Measure the branching ratio; for example $Br(\bar{B}^0 \to D^{*+}\ell^-\bar{\nu})$. This is not the only, but certainly the easiest exclusive channel to use. (2) We need the lifetime of the $\bar{B}^0$ (not an average lifetime) to extract $\Gamma(\bar{B}^0 \to D^{*+}\ell^-\bar{\nu})$. (3) We need to know the integrated form factor α that describes the hadronic current in the decay amplitude that creates the D^{*+}. This comes from theory but needs to be checked experimentally using methods I will describe: (1) we can do, (2) is crude at this point, and (3) will require more data.

The branching ratio $\bar{B}^0 \to D^{*+}\ell\bar{\nu}$ is measured using a very clever technique, first implemented by ARGUS. It is again a technique unique to the $\Upsilon(4S)$ which exploits the fact that the B's are produced nearly at rest. We are going to partially reconstruct the decay; "partially" since the neutrino will always escape unobserved. First a D^0 candidate is found in an hadronic event with a lepton, $1.4 < p_\ell < 2.4$ GeV/c, using the decay modes $D^0 \to K^-\pi^+$ or $D^0 \to K^-\pi^+\pi^-\pi^+$. The candidate D^0's are combined with other pions in the event to form a D^{*+}. The reconstruction of the D^{*+} is extremely clean. The phase space available for the pion in the decay $D^{*+} \to D^0\pi^+$ is very small since the mass difference between the D^{*+} and the D^0 is only 145.45 MeV and the resolution on the mass difference is 0.8 MeV (to be compared with a resolution of 12 MeV for the D^0 mass). Figure 15 shows a D^0 signal from CLEO with an identified lepton in the event before the $D^{*+} - D^0$ mass difference cut. D^*'s from continuum events are supressed by requiring that the momentum of the D^* be less than $M_B/2$.

We now have an event with a lepton and a D^{*+}, and we want to try to reconstruct a B.

If the B mesons were exactly at rest, then true $D^*\ell$ combinations from B decay would give a narrow peak at zero when the missing mass recoiling against the $D^*\ell$ candidate was plotted. In effect we reconstruct the B by reconstructing the missing neutrino. The missing mass squared is just:

$$MM^2 = (E_B - (E_{D*} + E_\ell))^2 - (\vec{p}_B - (\vec{p}_{D^*} + \vec{p}_\ell))^2.$$

The energy of the B meson is E_{beam} which we can substitute for E_B. We don't know $\vec{p}_B$ but we know that in magnitude it is small. We ignore it and the effect is to broaden the missing mass distribution. Figure 16 shows the missing mass distribution from CLEO for right sign $D^{*+}\ell^-$ (and charge conjugate) combinations and for wrong sign $D^{*\mp}\ell^{\mp}$ combinations and there is clear evidence for a B^0 signal. There are backgrounds to this procedure. The dominant background appears to be either the decay $B \to D^*(2420)\ell^-\bar{\nu}$ where $D^*(2420) \to D^{*+}\pi$ and the pion is not detected or $B \to (D^*\pi)_{non-resonant}\ell^-\bar{\nu}$. This gives a peak in the missing mass distribution at a slightly high value of MM^2, giving the distribution a high MM^2 shoulder. Other backgrounds include continuum events, cascade decays where the D^{*+} is from one B in the event and the lepton is from the charm decay of the other B, mixed events to where the lepton is from a B that mixed and the D^{*+} is from the other B, and fakes.

Once the background has been subtracted, the remaining events can be used to extract the branching ratios

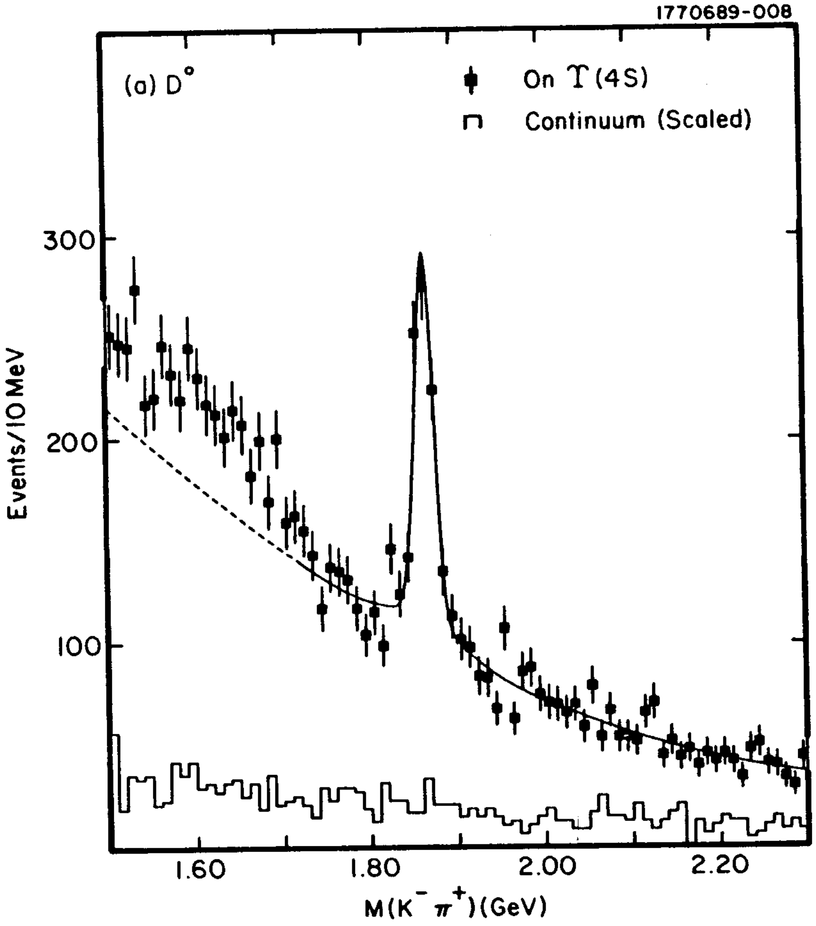

Figure 15. The invariant mass distribution for D^0 candidates in events with an identified lepton from CLEO.

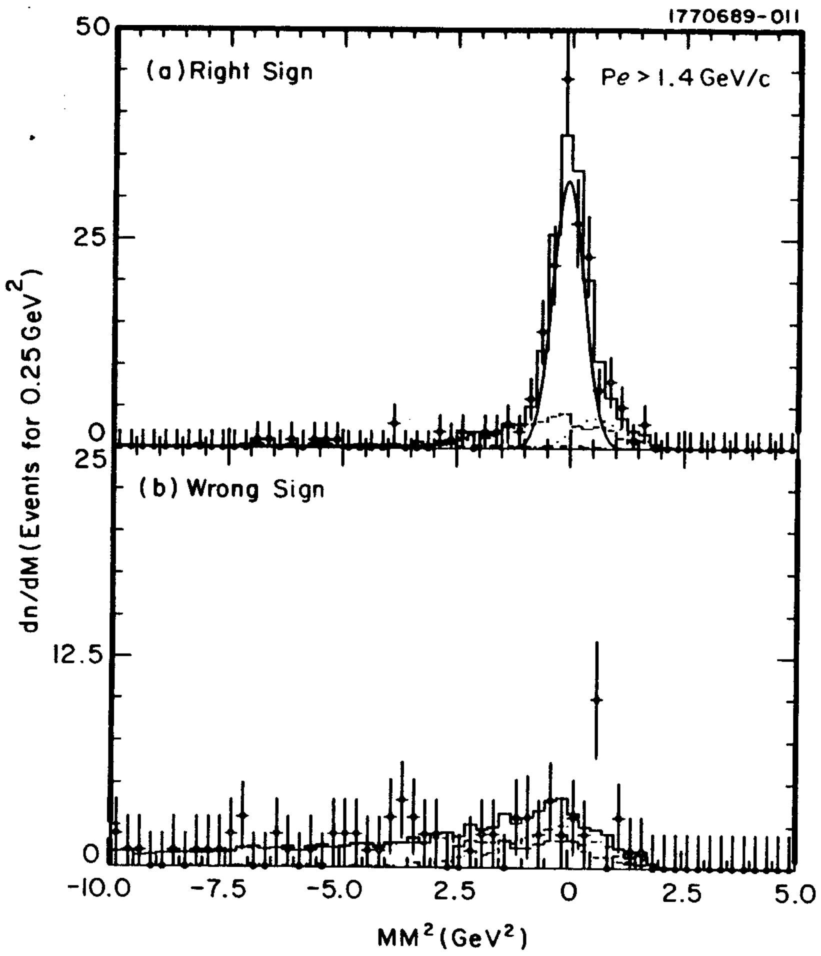

Figure 16. CLEO data for exclusive $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ decays (a) right sign, and (b) wrong sign events.

$$\begin{aligned} Br(\bar{B}^0 \to D^{*+}\ell^-\nu) &= (4.6 \pm 0.5 \pm 0.7)\% \ \ CLEO^{[35]} \\ &= (5.4 \pm 0.9 \pm 1.3)\% \ \ ARGUS^{[36]} \ . \end{aligned}$$

An interesting fact to note is that the average inclusive B semi-leptonic branching is 10.4%, so if the inclusive B^0 semi-leptonic branching ratio is close to the same as B^+, then $D^{*+}\ell^-\bar{\nu}$ is the dominant semi-leptonic decay mode. In fact, $D^*\ell\nu$ and $D\ell\nu$ account for 2/3 of the inclusive semi-leptonic branching ratios.[37]

Our goal, recall, was to extract V_{cb}. Various form factor models predict

$$\begin{aligned} \Gamma(\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}) &= K|V_{cb}|^2 * 10^{12}s^{-1} \\ &= \frac{Br(\bar{B}^0 \to D^{*+}\ell^-\bar{\nu})}{\tau(B^0)} \end{aligned}$$

where K varies between 22 and 26.[30][31][32]

What do we use for $\tau(B^0)$? We could use the average B lifetime determined by PEP and PETRA, or we could use the Mark II result mentioned last time which has rather large errors. There is a third option, which also has large errors, although smaller than errors on the Mark II method. Both CLEO and ARGUS have used the missing mass technique just described for $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}$ to determine other exclusive semi-leptonic branching ratios, such as $B^+ \to \bar{D}^0\ell^+\nu$ and $B^0 \to D^-\ell^+\nu$. To extract the lifetime ratio from the semi-leptonic branching ratio relies on the assumption that $\Gamma(B^+ \to \bar{D}^0\ell^+\nu) = \Gamma(B^0 \to D^-\ell^+\nu)$ due to the absence of final state interactions. Since

$$\begin{aligned} Br(B^+ \to \bar{D}^0\ell^+\nu) &= \frac{\Gamma(B^+ \to \bar{D}^0\ell^+\nu)}{\Gamma_{TOT}(B^+)} \\ &= \tau_{B^+}\Gamma(B^+ \to \bar{D}^0\ell^+\nu) \end{aligned}$$

we easily get

$$\frac{Br(B^+ \to \bar{D}^0\ell^+\nu)}{\tau_{B^+}} = \frac{Br(B^0 \to D^-\ell^+\nu)}{\tau_{B^0}}$$

or

$$
\begin{aligned}
\tau_{B^+}/\tau_{B^0} &= \frac{Br(B^+ \to \bar{D}^0 \ell^+ \nu)}{Br(B^0 \to \bar{D}^- \ell^+ \nu)} \\
&= 1.00 \pm 0.23 \pm 0.14 \quad ARGUS^{[38]} \\
&= .89 \pm 0.19 \pm 0.13 \quad CLEO^{\;[37]}.
\end{aligned}
$$

We can then use this to extract the B^0 lifetime from the average lifetime determined at PEP and PETRA. We can now extract $|V_{cb}|$ from the $D^*\ell\nu$ exclusive branching ratio and get

$$
\begin{aligned}
|V_{cb}| &= .039 \pm .004 \pm .005 \quad CLEO \\
&= .043 \pm .006 \pm .005 \quad ARGUS.
\end{aligned}
$$

Again, the first error quoted is the statistical plus systematic error from the branching ratio measurement and the second error includes model uncertainties and the uncertainty in τ_{B^0}.

To extract this result, we had to rely on the theoretical predictions of the form factors for the decay $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}$ which were hidden in the factor K. Why should we trust the theorists? In fact, we have every reason not to trust them because, if we are to believe recent results from E691,[39] the theoretical form factors predicted for the analogous decay: $D^+ \to \bar{K}^{*0}e^+\nu_e$, are wrong! I am being unfair. In the case of the $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}$ decay, it is thought the theoretical form factors are rather good; better than the charm case since we have a heavy quark in the final state. However, the question of form factors will come up again when we try to intrepret our $b \to u$ data, so I want to discuss them now.

A very nice introduction to form factors can be found in the review of Gilman and Singleton[40] and I will borrow from that. Consider the semi-leptonic decay of a pseudoscalar meson: $M \to me\bar{\nu}$ as shown in Fig. 17. The decay rate is given by

$$
d\Gamma(M \to me\bar{\nu}) = \frac{1}{2M}|A(M \to me\bar{\nu})|^2 d\pi_3
$$

where $d\pi_3$ contains the final state phase space factors and

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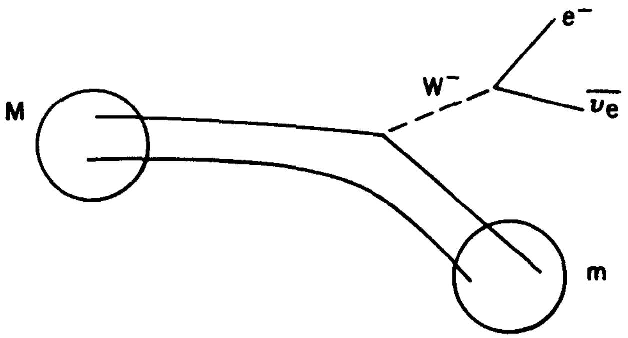

Figure 17. Feynman diagram for the weak decay $M \to me\bar{\nu}$.

$$A(M \to me\bar{\nu}) = \frac{G_F}{\sqrt{2}} V_{Qq} L^{\mu} H_{\mu}.$$

V_{Qq} is just the CKM matrix element for the $Q \to q$ transition, and L^{μ} and H_{μ} are the leptonic and hadronic final state currents respectively. L^{μ} we know:

$$L^{\mu} = \bar{u}_e \gamma^{\mu}(1 - \gamma_5) v_{\nu}.$$

The matrix element for the hadronic current is not so simple, particularly for a vector meson in the final state. H is usually expressed in terms of 3 amplitudes corresponding to the 3 helicity states of the virtual W, ($H_{\pm}$ and H_0,) for a vector final state, and is described by a single amplitude for a pseudoscalar final state (when m_{ℓ} is small).

The full decay amplitude is given by a very complicated function of the H's and the variables of the final state phase space, and I refer the interested reader who wants to see the details to the Gilman and Singleton paper. The helicity amplitudes themselves, the H's, are linear combinations of the form factors which one calculates from theory. There are 3 form factors for the vector decay and 1 for the pseudoscalar decay giving 4 in all and the decay rate is a very complicated function of those form factors. These form factors describe our lack of ability to calculate QCD.

To date, we have been testing the theoretical predictions for the form factors in B decay by integrating the transition probability over all variables (except possibly the lepton energy spectrum). That is the procedure I described for determining V_{cb}. There has been a slight improvement on that in the decay $B \to D^* \ell \nu$. The ratio of transverse to longitudinal polarization of the D^* has been measured, which is a measure of the ratio of the integrated longitudinal to transverse helicity amplitudes. What one really wants to do, however, is measure the form factors directly, without integrating over all the final state variables.

In order to do this one must fit the differential decay rate:

$$d\Gamma(M \to me\bar{\nu}) = \frac{1}{2M} |A(M \to me\bar{\nu})|^2 d\pi_3$$

A priori the differential decay rate is a function of 9 variables in $d\pi_3$,

$$d\pi_3 = (2\pi)^4 \delta^4(P - p - p' - k) \Pi_f \frac{d^3 k_f}{(2\pi)^3 2E_f}$$

but energy and momentum conservation as expressed in the δ function take care of 4 of the variables leaving 5 to fit to. E691 has done a nice analysis where they fit to the differential decay distribution for $D^+ \to \bar{K}^{*0} e^+ \nu_e$ and extracted the form factors using the full information of the angular distribution. We need about twice the current data sample to be able to do a similar analysis for the decay $\bar{B}^0 \to D^{*+} \ell^- \bar{\nu}$. Once one is in a position to compare the individual form factors with the theoretical models, one can be much more confident about extracting CKM matrix elements from exclusive semi-leptonic decays.

C. Charmless Semi-leptonic B Decays

I now want to switch from determinations of V_{cb} to the determination of V_{ub} by CLEO and ARGUS. V_{ub} is a crucial piece of the puzzle that explains CP violation. If any one of the elements of the 3 x 3 CKM quark mixing matrix is zero, then it cannot describe the observed CP violation in K decays. Neither CLEOnor ARGUS has a good measurement of V_{ub} yet, mostly because of large theoretical uncertainties, but both agree that $V_{ub} \neq 0$.

The most satisfying way to search for $b \to u$ transitions is to exclusively reconstruct a sample of $b \to u$ decays. The theoretical interpretation might be difficult, depending on the mode, but it would be experimentally unambiguous. The most sensitive way to look for evidence that the coupling of the b quark to the u quark is different from zero, however, is to look in the inclusive single lepton spectrum for leptons (electrons or muons) from the B semi-leptonic decay which are kinematically incompatible with coming from the charm decay of the B meson. Recall that the b quark will preferentially turn into a c quark when it weakly decays, but charmed quarks are heavy. The lightest mass particle containing a charmed quark is a D meson which has a mass of 1.8 GeV. The technique I will describe relies on the fact that the minimal hadronic mass in a charm decay of the B meson is the mass of the D meson, while in a charmless decay of the B meson, the final state hadronic mass can be as light as the mass of a pion (139 MeV). This difference in final state mass is reflected in the momentum of the lepton from the decaying B. Leptons from the decay $B \to D\ell\nu$ must have a momentum of less than 2.46 GeV/c in the lab, while in the decay $B \to \pi\ell\nu$, the lepton momentum can extend up to 2.7 GeV. This is schematically illustrated in Fig. 18. Conceptually, this experiment is no different from examining the endpoint spectrum of tritium beta decay for evidence of neutrino mass.

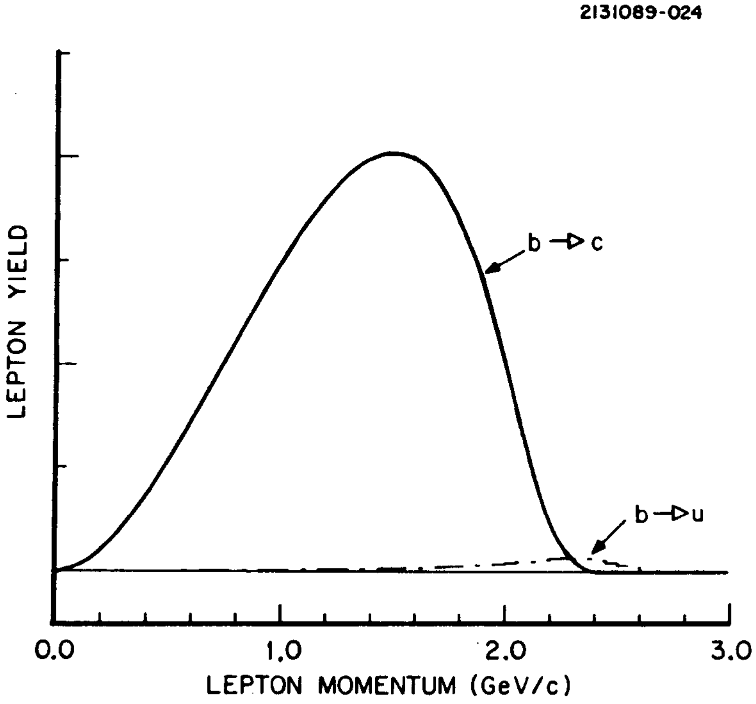

Figure 18. Predicted lepton spectrum for semi-leptonic B decays. The solid curve is the spectrum for $b \to c$ decays, the dotted curve is for $b \to u$ decays.

Most leptons in the inclusive lepton spectrum at $\Upsilon(4S)$ energies that have momentum above 2.4 GeV will be from continuum events where $e^+e^- \to q\bar{q}$ with $q = u, d, c, s$. In order to supress contributions from the continuum, both ARGUS and CLEO cut on the event shape. This supression takes advantage of the fact that the B decays nearly at rest so its decay products are isotropic. Continuum events produce particles traveling with a substantial boost and the decay products tend to be collimated along the flight path. Figure 19 shows an expanded view of the CLEO lepton spectrum at the $\Upsilon(4S)$ after a cut on the event shape. You can see there are leptons in the region above 2.46 GeV - the endpoint for $b \to c$ decays, and there are leptons above 2.7 GeV, the kinematic limit for leptons from B decay. This is because there are still real leptons (and fake leptons - misidentified hadrons) from continuum events. The continuum has been supressed, but there are still plenty of events.

At this point CLEO and ARGUS branch in the way they do the analysis. CLEO removes the continuum contribution by taking the continuum data sample from the running below the $\Upsilon(4S)$, scaling it by the difference in luminosity and energy, fitting it, and subtracting it from the lepton sample. Figure 20 shows the lepton spectrum from CLEO with the continuum contribution (and fakes) subtracted, and you see there are still events in the endpoint region, but above 2.7 GeV there are no events, which is a cross check the continuum was subtracted correctly.

The ARGUS analysis differs from CLEO's in that they continue to supress the contribution from the continuum using additional cuts, so that the eventual continuum subtraction is smaller in magnitude. They use a more severe shape cut, and they require missing momentum in the event of $1.0 < p_{miss} < 3.5$ GeV/c to correspond to the escaping, undetected neutrino. Figure 21 shows their lepton spectrum above 2 GeV[41] and also indicates the small continuum contribution.

Both experiments extend their search for excess leptons down into the region where $b \to c$ transitions are allowed but very phase space supressed, and use models of $b \to c$ decays to estimate how much $b \to c\ell\nu$ contaminates their sample. ARGUS quotes a lepton excess of 77 ± 13.4 out of a total of 132 events in the $2.3 < p_\ell < 2.6$ GeV momentum region.[42] They also have a separate sample of dilepton events where they see an excess of 14 ± 5 events out of a total of 21.[41] CLEO divides the endpoint region into 2 bins in momentum, $2.2 - 2.4$ GeV/c and $2.4 - 2.6$ GeV/c, and quotes an excess of $61.6 \pm 29.8 \pm 29.1$ events in the lower bin and $70.4 \pm 20.3 \pm 10.4$ in the upper bin out of 813 and 349 events in each bin before continuum subtraction.[43] The subtractions are large, but it seems beyond doubt that there is a source of leptons at the $\Upsilon(4S)$ that have

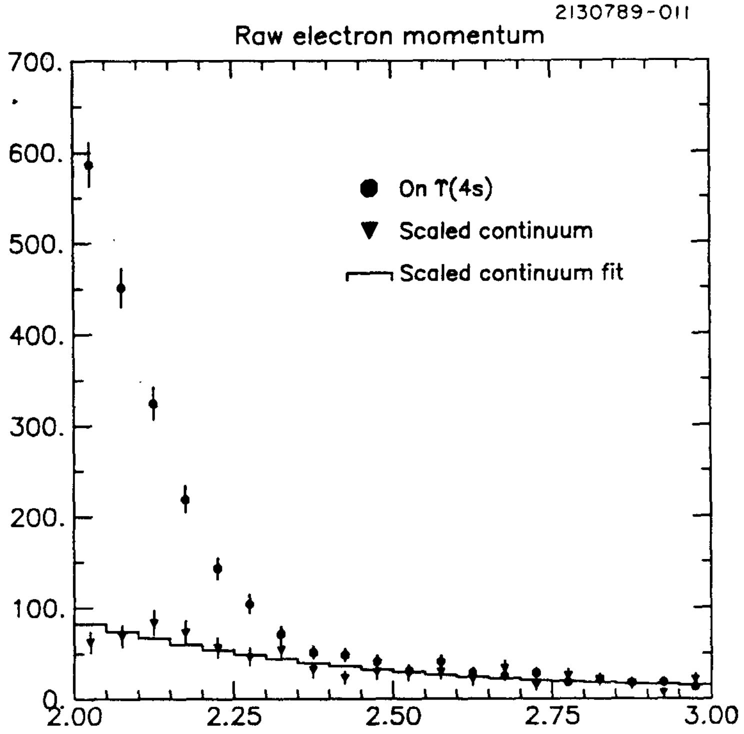

Figure 19. The yield of electrons in the endpoint region from CLEO before continuum subtraction.

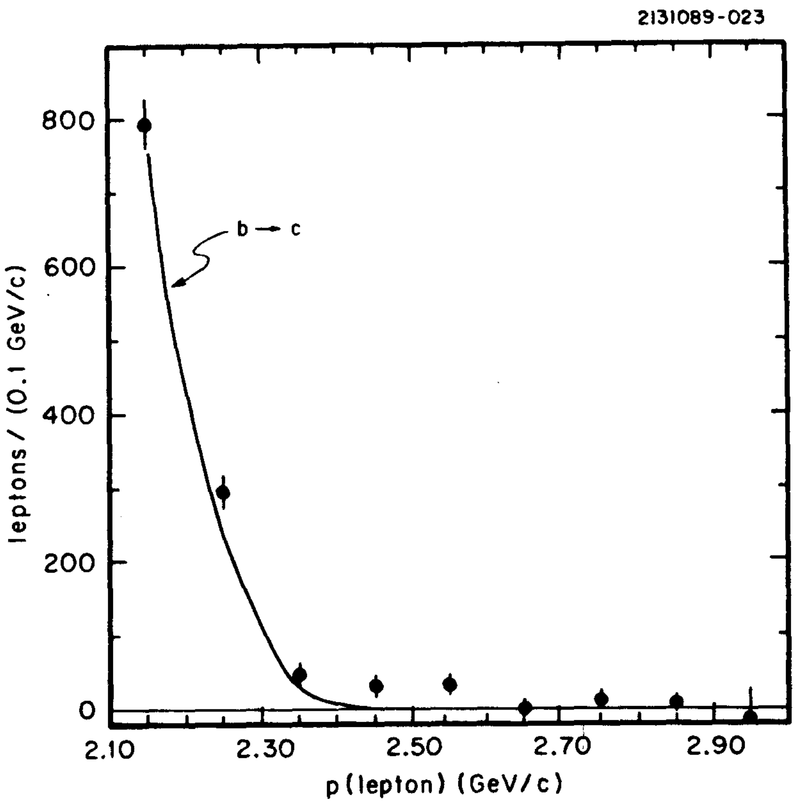

Figure 20. The yield of leptons in the endpoint region from CLEO after all subtractions. The expected $b \to c$ contribution is indicated as a smooth curve.

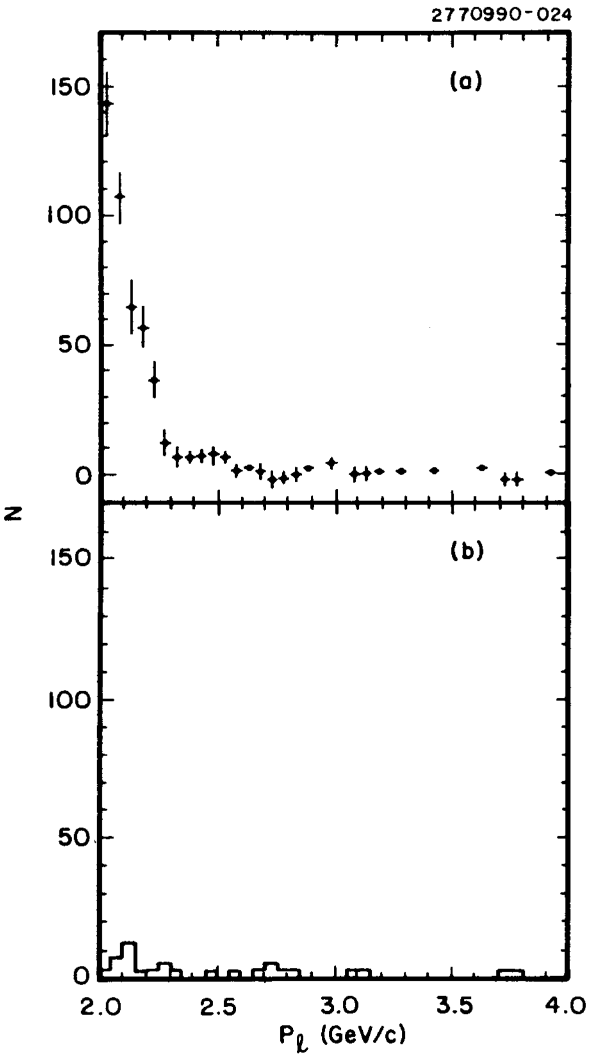

Figure 21. ARGUS lepton yield in the endpoint region for (a) $\Upsilon(4S)$ data after continuum subtraction and (b) scaled continuum.

a momentum too large to be accounted for by $b \to c$ decays. Is it $b \to u$? If we assume that $\Upsilon(4S) \to B\bar{B}$ 100% of the time, then the leptons must come from B decays. However, non-$B\bar{B}$ decays of the $\Upsilon(4S)$ could produce leptons in this momentum range. Without knowing more about the non-$B\bar{B}$ decays of the $\Upsilon(4S)$, we can't put any meaningful limits on contributions it might make to the inclusive lepton spectrum. It is worth noting that the absence of an excess of leptons above 2.7 GeV rules out large contributions from direct $\Upsilon(4S)$ decays. The other thing worth noting is that ARGUS was able to fully reconstruct an event from their sample with $p_\ell > 2.3$ GeV and they reconstruct a $b \to u$ decay.[42]

The excess of leptons cannot be accounted for by any known source and it is assumed it results from $b \to u$ transitions. Now, to extract a value of V_{ub} from the event excess requires a theoretical model. This turns out to be quite problematic. Table 4 lists the value of $|V_{ub}|V_{cb}|^2$ derived by CLEO and ARGUS from their data, and while the experiments agree quite well, the theories do not.

Table 4.

Model	$\|V_{ub}/V_{cb}\|^2 * 10^2$	
	CLEO	ARGUS
ACCMM[28]	$.8 \pm 0.2$	1.0 ± 0.2
ISGW[30]	2.2 ± 0.6	3.2 ± 0.7
WSB[31]	1.3 ± 0.4	1.4 ± 0.4
KS[32]	0.9 ± 0.2	0.8 ± 0.2

Note that all these theories agree on the value of V_{cb} extracted from data.

It is not really surprising that the free quark model (ACCMM) does not work. We are examining the endpoint of the spectrum, just where we expect resonances to be important. However, the form factor models also disagree, leaving a large uncertainty in the actual determination of V_{ub}. How can this situation be improved?

The key to improving the determination of V_{ub} lies in more experimental data and a better understanding of the theoretical models. Figure 22 shows the Dalitz plot for semi-leptonic B decays and the experiments currently are sensitive to only a very restricted region of the Dalitz plot. The values of V_{ub} that are extracted from the data depend critically on the details of how a particular theory chooses to populate the hadronic states such as $B \to \pi\ell\nu$, $B \to \rho\ell\nu$, $B \to \omega\ell\nu$, that contribute most significantly in the endpoint region. The hope

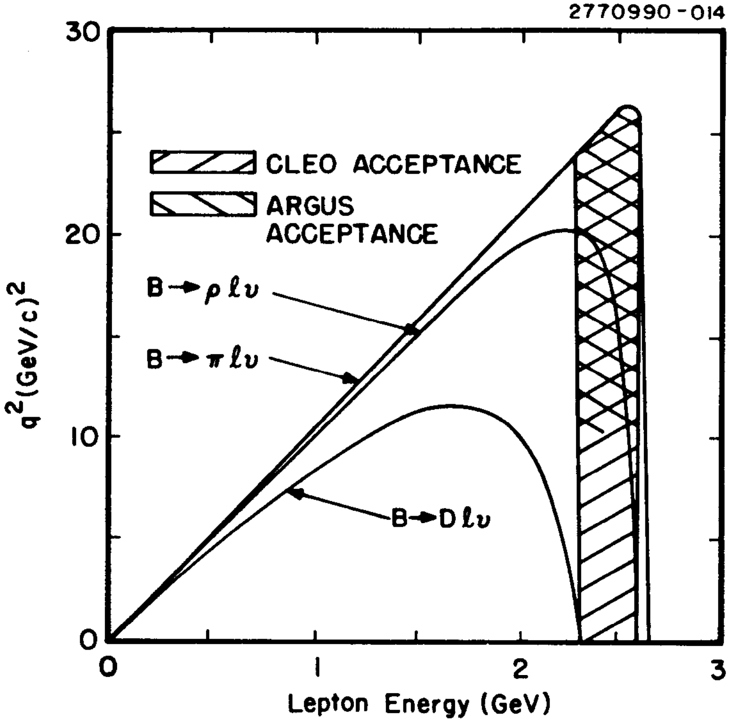

Figure 22. The Dalitz plot for the B semi-leptonic decay. The kinematic boundaries are shown for $B \to \pi\ell\bar{\nu}$, $\rho\ell\bar{\nu}$ and $D\ell\bar{\nu}$. The approximate acceptance regions are shown for ARGUS and CLEO.

is that Mr.'s Isgur and Wise are telling us that if we measure the form factors in the Cabibbo supressed $D \to \pi\ell\nu$ and $D \to \rho\ell\nu$ decays, we can in a model independent way extract the form factors (over some range of the Dalitz plot at least) for $B \to \pi\ell\nu$ and $B \to \rho\ell\nu$.[34] This would be a great step forward since it is unlikely that any experiment in the forseeable future will be able to do the kind of form factor analysis on the charmless B decays that was discussed for $B \to D^*\ell\bar{\nu}$.

D. $B^0 - \bar{B}^o$ Mixing

I want to conclude this section on semi-leptonic B decays with a discussion of the phenomenon of mixing in the neutral B meson system. According to our standard model picture of the weak interactions of quarks, the neutral B mesons should mix, and they do. Mixing means that a B^0 meson can turn into a $\bar{B}^0$ meson via the second order weak process as shown in Fig. 23. Since both the b and d quarks can couple to u, c, and t quarks via the weak interaction, the B^0 meson "decays" into a pair of virtual W bosons which then reappears as a $\bar{B}^0$. The mixing of the neutral B mesons is observable if the rate for a B^0 to mix into a $\bar{B}^0$ is comparable to the rate at which the B decays.

The cleanest measure of mixing would be a sample of fully reconstructed B^0B^0 or $\bar{B}^0\bar{B}^0$ events since they could exist only if mixing had occurred. Full event reconstruction is extremely difficult, and to date there exist only a few fully reconstructed mixed events from ARGUS. The best measurement of mixing comes from using inclusive methods where the flavor of the b quark that decays is tagged using a lepton. When I say tag the flavor, I mean that the sign of the lepton emitted tells whether it was a b or an anti-b quark that decayed. Leptons are particularly useful since, as we have learned, 20% of the B decays are to a lepton, leptons are easy to detect, and at high momentum (or high transverse momentum if mixing is being measured at E_{CM} above the $\Upsilon(4S)$), there is low background.

To measure mixing one wants to measure the ratio of the probability that a particle born as a B^0 will decay as a $\bar{B}^0$, to the probability it will decay as a B^0. In the absence of background, this can be expressed as a ratio of same sign to opposite sign dilepton events. We define a mixing ratio:

$$r = \frac{N(\ell^+\ell^+) + N(\ell^-\ell^-)}{N(\ell^+\ell^- \ from\ B^0\bar{B}^0\ decay)}.$$

Whereas counting the number of same sign and opposite sign dilepton events from B^0 and $\bar{B}^0$ decays is simple in practice, there are some serious experimental difficulties.

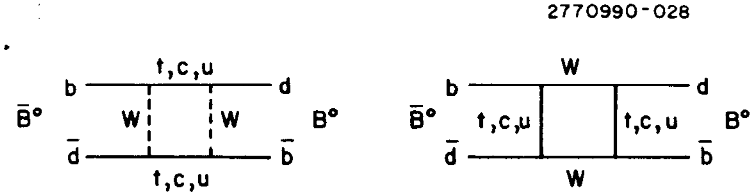

Figure 23. Lowest order Feynman diagrams describing mixing in the neutral B meson systems.

(1) Fakes: are the leptons in our 2 lepton event really leptons, or are they misidentified hadrons?

(2) Did both leptons in the event come from B decay? One B can decay to a lepton and the other B can decay to a D meson which then decays to a lepton. These cascade decays contribute like sign dileptons even in the absence of mixing so this background is particularly insidious.

(3) A severe problem for mixing measurements at hadron machines is leptons from π and K decays in flight.

(4) The $\Upsilon(4S)$ decays into either a neutral ($B^0\bar{B}^0$) or charged (B^+B^-) pair of mesons. Charged B mesons can decay to leptons and contribute to the denominator of the mixing ratio r.

(5) Above the $\Upsilon(4S)$ at higher energy e^+e^- or $p\bar{p}$ machines, one is measuring mixing of an unknown mixture of B_d and B_s mesons and the denominator of r contains contributions from all bottom hadrons, including charged mesons and baryons.

In 1987 UA1 was the first experiment to claim an observation of $B\bar{B}$ mixing[44] based on an excess of like sign dilepton events in $p\bar{p}$ collisions. Since then both CLEO and ARGUS have measured mixing. CLEO and ARGUS measure $B^0_d\bar{B}^0_d$ mixing, all other experiments measure a combination of B_d and B_s mixing.

At ARGUS and CLEO the basic analysis for mixing is the same. Hadronic events are selected that have 2 leptons where both leptons are required to have a momentum between 1.4 and 2.4 GeV/c. The lower cut supresses cascade decays where one lepton is from a B, the other from a D, and the upper cut supresses continuum background since it is close to the kinematic upper limit for leptons from B's. There is also an opening angle cut between the two leptons to supress photon conversions and fakes from continuum jets. After these cuts each experiment has approximately 70 like sign events and 400 unlike sign events. Of the roughly 70 like sign events that each experiment has, cascade decays and fakes account for roughly half of them, and must be subtracted. Table 5 gives the numbers of like sign and opposite sign dileptons from ARGUS.[45]

Table 5.

	$N(\ell^{\pm}\ell^{\mp})$	$N(\ell^{\pm}\ell^{\pm})$
$\Upsilon(4S)$	413	64 ± 10
Fakes + Continuum + Cascades + ψ	31	29
Signal	382 ± 22	35 ± 11

To calculate r, the contribution of the opposite sign dilepton sample from charged B decays must be subtracted. This is difficult since the fraction of the total number of dileptons coming from charged B decays depends on quantities we don't know very well. The number of dileptons from charged B's depends on

(1) The ratio of the number of charged to neutral B's produced at the $\Upsilon(4S)$, f_+/f_o, and which we take to be 1.

(2) The ratio of the semi-leptonic branching ratios, b_+/b_o, which is equal to the ratio of lifetime of the charged and neutral B's.

Using $f_+b_+^2/f_ob_o^2 = 1.2$ we get

$$\begin{aligned} r &= 0.19 \pm 0.06 \pm 0.06 \quad CLEO^{[46]} \\ &= 0.22 \pm 0.07 \pm 0.06 \quad ARGUS^{[45]} . \end{aligned}$$

ARGUS has also measured mixing using $D^*\ell\ell$ events which are events where the $D^*\ell$ have been partially reconstructed to give a $\bar{B}^0$ as described earlier, and another lepton is required in the event. This method eleminates any contamination from charged B's so that while it is statistically weaker, the systematic errors are smaller, giving

$$r = 0.24 \pm 0.12 \pm 0.02 \quad ARGUS.^{[45]}$$

We conclude that the mixing of neutral B mesons is large. A particle born as a B has a 20% chance of turning into a $\bar{B}^0$ before it decays. We can now play the game of extracting V_{td} from this measurement. To do this we need to relate the observed ratio of same sign to opposite sign dilepton events from B^0 decays, to the theoretical estimates of the box diagrams responsible for mixing. The most convenient quantity to define is

$$Z = \frac{Br(\bar{B}^0 \to B^0 \to X\ell^+\nu)}{[Br(\bar{B}^0 \to B^0 \to X\ell^+\nu) + Br(\bar{B}^0 \to X\ell^-\nu)]}$$

which is just the probability that an isolated $\bar{B}^0$ meson will decay as a B^0. This can be calculated from the box diagrams[47] as

$$Z = \frac{(\Delta M/\Gamma)^2}{2 + 2(\Delta M/\Gamma)^2}$$

where

$$\frac{\Delta M}{\Gamma} = \frac{32\pi}{3} \frac{|V_{td}V_{td}^*|^2}{|V_{cb}|^2} \frac{B_B f_B^2 \eta_2 M_t^2}{M_b^4} \Phi[\frac{M_t}{M_w}] \quad .$$

$\Delta M/\Gamma$ contains many terms that are not well known, among them the B meson structure constant $B_B f_B^2$, and M_t^2. We still need to relate Z to the observed ratio of same to opposite sign dileptons. On the $\Upsilon(4S)$, the $B^0\bar{B}^0$ state is P-wave and Bose statistics inhibit mixing. The B's must mix coherently (always remain a $B^0\bar{B}^0$ pair) and it is only when one B decays that the other is free to mix independently. As a result, the like sign dilepton rate is actually supressed on the $\Upsilon(4S)$. We find on $\Upsilon(4S)$: $r = Z/(1-Z)$. If the b quarks are not produced in a coherent state,

$$r = \frac{2Z(1-Z)}{Z^2 + (1-Z)^2}.$$

We now have a relation between r (the measured quantity) and V_{td}. We can only really put a limit on the product $M_t^2|V_{td}V_{td}^*|^2$. If we cheat a little and use the unitarity of a 3 generation CKM matrix to put an upper limit on V_{td} and use the upper limit on the top quark mass of $M_t \lesssim 200$ GeV from EW radiative corrections, we get $.004 < V_{td} < .02$.[48] Two last points I would like to mention. (1) Experiments at PEP[49] and UA1[44] have seen evidence for mixing in data that contains both B_d and (we assume) B_s mesons. These experiments universally agree that they see more mixing (more like sign dilepton pairs when backgrounds from cascades, fakes, and decays in flight are removed) than can be accomodated by B_d mixing alone. The B_s should be produced at these energies and it should mix even more strongly than B_d (because V_{ts} is expected to be larger than V_{td} since it is only one generation off diagonal in the CKM matrix instead of two). (2) When B_s mixing has been well measured (which is a very difficult proposition since as $\frac{\Delta M}{\Gamma}$ gets large, $Z \rightarrow 1/2$, and $r \rightarrow 1$ independent of Z!), one can extract $|V_{td}|^2 f_{B_d}^2 / |V_{ts}|^2 f_{B_s}^2$ independently of M_b^2, B_B and M_t^2, if it is still unknown.

4. B Physics in the Future

In these final sections, I want to concentrate on the future, and I will do this in two parts. First, I want to talk about what to expect in the very near future: this year, next year and the year after from LEP/SLC, the Tevatron and CLEO II and ARGUS. LEP and SLC are opening a window on how the b quark couples to the Z^0, and if you recall from Chapter 2, a large (6nb) cross section and high energy will allow them to do physics that lower energy experiments have not done. CDF is just beginning to learn how to do B physics, and I think they will contribute a lot, and CLEO II has just turned on with a new state of the art detector and a machine that plans to scale new heights in luminosity, and is advertising B physics at the $\Upsilon(4S)$ with an order of magnitude with more precision than ever before. I want to discuss a few of what I consider to be the most important experiments these groups will do in the next few years. Let me give my usual disclaimer that I make no pretenses at being comprehensive in this review. It is rather a selection of topics that I personally find interesting.

The final chapter will be on the far future, and that is how one might measure CP violation in the B meson system. That is a subject that could take volumes to discuss. I will simply present a collection of what I think are interesting and relevant facts about CP violation in the B meson system, how it might manifest itself, and how one might measure it.

A. The Near Future

Once the standard electro-weak model is defined by precision measurements of α, G_F and M_Z, all of the coupling strengths between the matter fields of quarks and leptons, and the gauge bosons are predicted. These predictions need to be tested, and while measuring the vector and axial vector coupling between the b quark and the Z^0 is not the easiest or most direct way to test the standard model, it needs to be done. One must verify that the b quark couples to the Z^0 like the lower member of a weak isodoublet, which is where it is supposed to sit. The standard model predicts

$$G_V = I_3 - 2Q sin^2\theta_w$$
$$G_A = I_3$$

for the vector and axial vector couplings of fermions to the Z^0, where I_3 is the third component of weak isospin, and Q is the charge of the fermion. The b quark is supposed to sit in the lower half of a weak isodoublet which it shares with the as yet undiscovered top quark, which gives $I_3 = -\frac{1}{2}$, $Q = -\frac{1}{3}$, so the SM predicts

$$G_A(b) = -\frac{1}{2}$$
$$G_V(b) = -.35 \qquad for\ sin^2\theta_w = .23.$$

Experiments at PEP, PETRA and TRISTAN have been able to measure G_A by looking at a forward-backward asymmetry in $e^+e^- \rightarrow b\bar{b}$ that originates from the interference between the photon and Z^0 exchange contributions to that process. The size of the asymmetry is proportional to G_A.

One method used to measure the forward-backward asymmetry is to tag b events with high p_t leptons and use the sign of the lepton to determine whether it came from a b or $\bar{b}$. One must correct for the neutral B's ability to mix. The asymmetry is then how many b ($\bar{b}$) quarks are produced forward vs backwards with respect to the $e^-(e^+)$ beam. Data from Tasso[50] in Figure 24 clearly show the effect of the forward-backward asymmetry, and from that one can extract $G_A(b) = -.6 \pm .25$.

At the Z^0 resonance, the partial width for the Z^0 to decay into $b\bar{b}$ pairs is

$$\Gamma_{b\bar{b}} = \frac{G_F M_Z^3}{6\pi\sqrt{2}}(G_V^2 + G_A^2).$$

Here, one can use the measured partial width and the SM value for G_A to extract G_V. It is not a good way to measure $sin^2\theta$, but it does verify the form of the vector coupling of the b quark to the Z^0. The method used to measure $\Gamma_{b\bar{b}}$ is straight forward. $b\bar{b}$ events are tagged with high p_t leptons, with the tagging efficiency determined from Monte Carlo. The ratio $\Gamma(Z \rightarrow b\bar{b})/\Gamma(Z - had)$ is just the ratio of the number of tagged events to the total number of hadronic events (both corrected for efficiency). This ratio times the measured hadronic width of the Z gives the partial width into $b\bar{b}$. The measured value[51] of

$$\Gamma_{b\bar{b}} = 353 \pm 25 \pm 25 MeV \qquad \text{(from L3)}$$

can then be used to extract

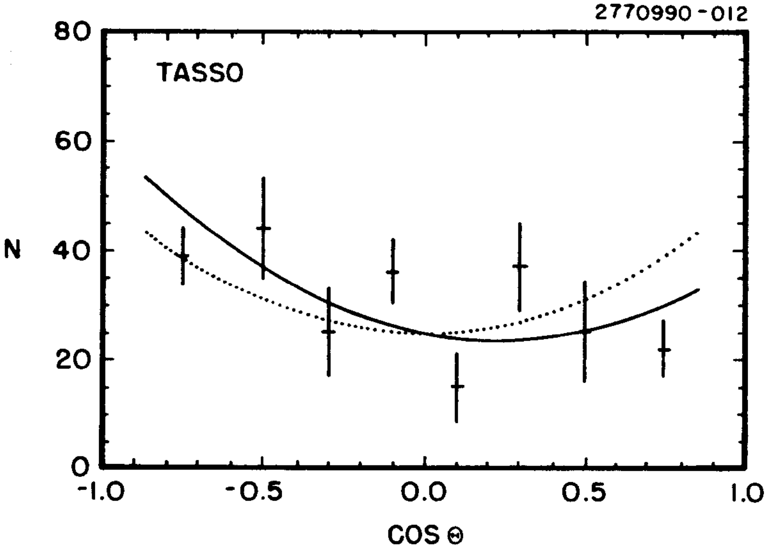

Figure 24. The angular distribution of $b\bar{b}$ events from TASSO. The dotted curve shows the prediction of pure QED, the solid one is the standard model fit - uncorrected for acceptance.

$$G_V^2 = .095 \pm .024 \pm .024$$

for the b quark. This is still somewhat crude, and it will get better, but I consider it real bread and butter electro-weak physics to measure those couplings. Already these measurements tell us unambiguously that the b quark lives in an isodoublet (as opposed to an isosinglet) and must have a partner!

One result we might hope for from SLC and LEP is the observation of the B_c: a $b\bar{c}$ meson. Unfortunately its production is highly suppressed relative to normal B production and it probably won't be seen soon.

A topic I hope we hear a lot about in the near future from both the Z^0 machines and the Tevatron is B_s. This is a particle for which there is only very indirect evidence to date. Experiments that measure mixing at high (> 10.58 GeV) energies want B_s because for reasonable assumptions about the amounts of B_d and B_s in their dilepton samples, the data favors more mixing than can be accomodated by the CLEO and ARGUS B_d mixing results, as we discussed at the end of the last chapter. Other indirect evidence for B_s comes from CUSB.[52] CLEO and CUSB accumulated approximately $100pb^{-1}$ of data each at the $\Upsilon(5S)$ in 1988, which is thought to be above $B_s\bar{B}_s$ threshold. CUSB observes 47.5 MeV photons from the decay $B^* \to B\gamma$. For decays $\Upsilon(5S) \to B^*B^* \to B\gamma B\gamma$, the β of the B^* is .21, resulting in substantial Doppler broadening of the monochromatic photon line. The observed line in the $\Upsilon(5S)$ data sample (shown in Fig. 25) is narrower than what one would expect from such rapidly moving B^*'s leading CUSB to infer they are seeing substantial B_s^* production where the $B_s^* - B_s$ mass difference is very close to the $B_d^* - B_d$ mass difference so the two photon lines are overlapping, with one line less Doppler broadened than the other. The net result is a narrower line.

I think it is about time to see the B_s directly!

I suspect B_s will be "discovered" at CDF or LEP. At CDF, perhaps they can fully reconstruct B_s using the highly supressed but very clean channel $B_s \to \psi\phi$. CDF has shown they can do a beautiful job on reconstructing ψ's, and they probably have enough events to have some of these decays in their data sample. I don't know if the background will be sufficiently worse than in the case of $B^- \to \psi k^-$ because of the addition of the extra kaon, that they will be unable to extract a signal. I would bet good money they are looking, and perhaps we will hear soon that they have seen it. In the next collider run where they are promising 10 times the luminosity and will have a silicon vertex detector to do vertex tagging, I think they should be able to exclusively reconstruct B_s for sure.

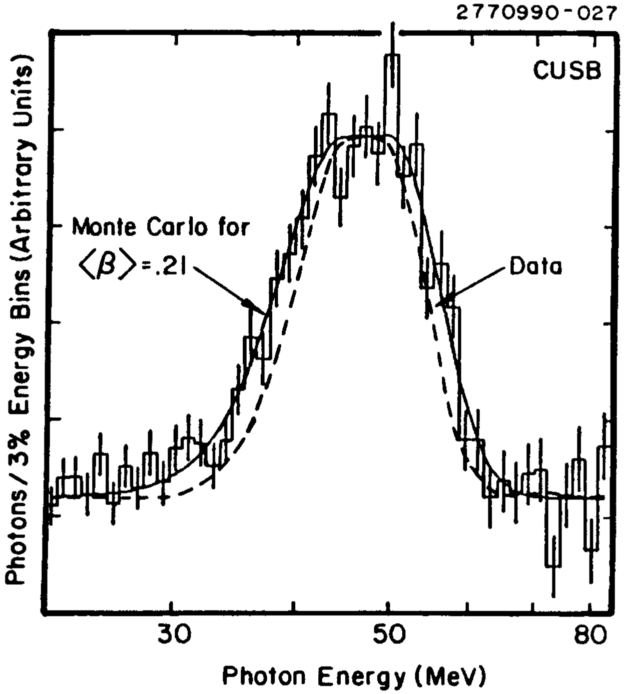

Figure 25. The evidence from CUSB for the B_s and B_s^* . The histogram and solid line are the Monte Carlo spectrum for $< B >= .21$. The dashed line is the result from the fit to the data.

Both CDF and LEP can look for B_s using D_s lepton signals (just as CDF uses $D^0\ell$ signals as evidence for B production). LEP will not have the data sample to do highly supressed ($Br \sim 10^{-3} - 10^{-4}$) modes for a while, but the environment is enough cleaner they will probably be able to use modes such as $B_s \rightarrow D_s\ell\nu$ more efficiently than CDF.

I think (hope) B_s will be observed, and its mass, lifetime, and mixing rate measured. With a silicon vertex detector and the projected $30pb^{-1}$ in the next collider run, CDF may have the first shot at the B_s lifetime (in addition to measuring the very important exclusive B^+ and B^0 lifetimes). LEP should be able to measure B_s mixing. Reliable and meaningful measurements will require a lot of work studying the B_s and B_d fractions produced from $b\bar{b}$ at 92 GeV so that B_d and B_s mixing can be reliably separated.

What about CLEO and ARGUS? What will they contribute to B physics in the next few years? ARGUS just installed an elegant new vertex detector on a 1.9 cm radius beampipe.[42] This vertex detector in many ways represents wire chamber technology carried to the ultimate limit. They claim that with this chamber they will be able to reconstruct D vertices. The median separation between two D mesons coming from B mesons is 120 μm at the $\Upsilon(4S)$ energy. If ARGUS succeeds in reconstructing a substantial number of D's with low background because they can use vertex information to separate the decay products from two D's in the event, they will substantially improve their ability to reconstruct B mesons. However, ARGUS was only given 2 months to run with the new chamber this year. They are now off for the rest of the year and I believe they do not know how much running time they will get next year as HERA turn on claims much of DESY's attention.

I will talk mostly about what CLEO will be doing for the next few years. CLEO II turned on in the fall of 1989 after an 18 month shutdown during which the entire detector, with the exception of the tracking chambers, was replaced. The central feature of the new CLEO II detector is a CsI calorimeter[53] covering 95% of 4π with an energy resolution of $\sigma_E/E = 1.5\%$ at the 5 GeV and 4.4% at 100 MeV. After a shakedown run of $150pb^{-1}$ on the $\Upsilon(3S)$, CLEO started taking data on the $\Upsilon(4S)$ in May. The goal of this run is to accumulate $1fb^{-1}$ of $\Upsilon(4S)$ data with an additional $500pb^{-1}$ on the continuum below the $\Upsilon(4S)$. This data sample will have 5 times the statistics of the data sample I discussed in the first three chapters. If one uses the number of fully reconstructed B mesons as a measure of the physics capability of the detector, CLEO II should be able to fully reconstruct on the order of 6000 B's from the new data sample compared to roughly 100 reconstructed in the previous sample. Part of the improvement is the larger data sample (which is yet to come), and part of it is the beautiful new calorimeter which allows CLEO II to have a resolution on neutrals similar to the resolution on charged particles. Figure 26 illustrates the capability of the calorimeter to see π^0's and η's.

Clearly, CLEO II will do everything CLEO I has done only with higher statistics. However, there are many qualitatively new analyses that we will be able to do.

(1) With the improved statistics we will be able to do a "proper" analysis of semi-leptonic B decays and extract the form factors by looking at the differential decay rate. The extraction of the form factors is very important to the measurements of CKM angles as was discussed in the previous chapter.

(2) We should be able to reconstruct exclusive $b \to u$ decays in hadronic channels such as $B \to \pi^+\pi^-$ or $B \to \pi\ell\nu$, $\rho\ell\nu$. The current limits on $B \to \pi^+\pi^-$ are about a factor of 3-4 above the theoretical expectation. This analysis will be aided by the crystal calorimeter since cuts on the event shape which are used to distinguish B decays from continuum will be more effective with the addition of neutral information. Observation of exclusive $b \to u$ decays may not aid in the determination of V_{ub} because of the model uncertainties discussed last time, but they will help to convince us that $b \to u$ is really there!

(3) Penguin decays of the B meson give effective flavor changing neutral currents which probe the electro weak interaction at the one-loop level. To lowest order, the GIM mechanism forbids flavor changing neutral currents, so that couplings like $b \to sZ^0$ cannot occur. However, higher order processes, as illustrated in Fig. 27, give an effective neutral current interaction. These diagrams result in decays like $B^- \to \bar{K}^{*0}\pi^-$, $K^-e^+e^-$ or $\bar{B}^0 \to K^-\pi^+$, $\bar{K}^0\rho^0$. These decays have not yet been seen although the limit on the BR for $\bar{B}^0 \to K^-\pi^+$ is very close to the theoretical expectation.[54]

Why are penguin decays so interesting? Clearly they are sensitive to the value of the CKM matrix element V_{ts}, although extracting the value of the matrix element is quite difficult given the theoretical uncertainties in predicting the exclusive branching ratio. Another reason that the penguins are interesting is that for certain final states like $\bar{B}^0 \to K^-\pi^+$, there are two diagrams that can contribute as shown in Fig. 27. The second diagram (Fig. 27b) is suppressed because of the one loop and the gluon, but it wins by a product of $V_{tb}V_{ts}^*$ which involves 0 and 1 generation CKM factors as opposed to the spectator diagram (Fig. 27a) which is proportional to $V_{ub}V_{us}^*$, and has 1 and 2 generation CKM factors. It is not clear which of the two diagrams will be dominant. The two diagrams can interfere and that interference is one way of getting CP violation in the B system.

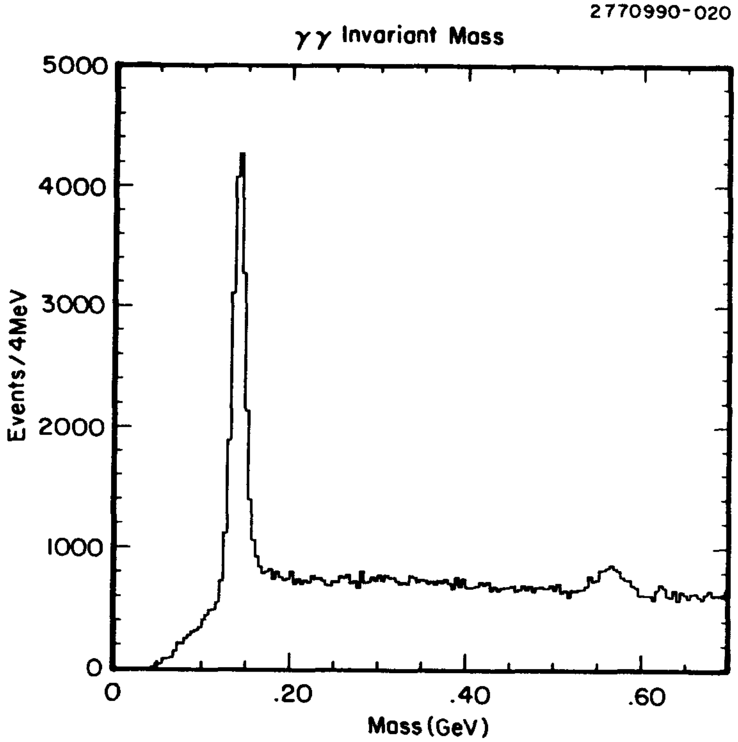

Figure 26. The invariant mass of photon pairs from hadronic events using the new CLEO II CsI calorimeter. A clear π^0 peak is evident, and also an η peak.

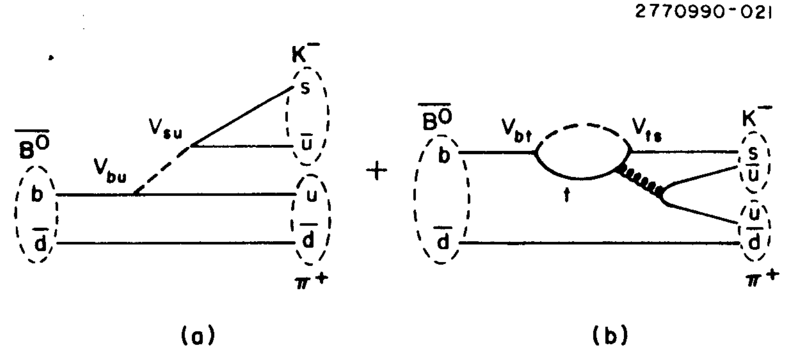

Figure 27. Lowest order diagrams for $b \to s$ decay where a) is a spectator diagram and b) is a penguin diagram.

(4) With a sample of 6000 or so exclusively reconstructed B's, and a sample possibly twice that size of low background partially reconstructed events (such as $B \to D^*\ell\nu$) CLEO II will have on the order of several hundred double tagged events where both B's are either partially or fully reconstructed. This will allow us to measure, for the first time, f_+/f_0; the ratio of the production cross section for charged and neutral B's at the $\Upsilon(4S)$. This works as follows. Suppose we reconstruct N_{xy} events where $B^+ \to x$, $B^- \to y$. Clearly

$$N_{xy} = f_+\sigma \int LdtBr(B^+ \to x)Br(B^- \to y)$$

where $\int Ldt$ is the integrated luminosity and σ is the $\Upsilon(4S)$ cross section. But,

$$N_x = f_+\sigma \int LdtBr(B^+ \to x)$$
$$N_y = f_+\sigma \int LdtBr(B^- \to y)$$

so we have

$$\frac{N_x N_y}{N_{xy}} = f_+\sigma \int Ldt.$$

σ and $\int Ldt$, the total cross section and the integrated luminosity, are known, and we have a measure of f_+. The reconstruction efficiency is not high enough to use double tagging to measure branching ratios to highly supressed modes, but we will be able to use double tagging to measure large branching ratios to "dirty" high background modes. The classic example of this technique was the Mark III measurement of the branching ratio $Br(D^0 \to K^-\pi^+\pi^0\pi^0) = 14.9 \pm 3.7 \pm 3.0\%$.[55] This is an enormous branching ratio but with two π^0's in the final state, it had eluded measurement due to large backgrounds, until it was found in double tagged D's from the ψ''.

(5) An experiment that is very important for measurements of CP violation in the B system is being done right now at CLEO and we hope to have a result soon. This is the measurement of the B^* production cross section above the $\Upsilon(4S)$. I will explain its relevance to CP violation in a few minutes. Let me first tell you what the experiment is.

The B^* is to the B meson what the D^* is to the D meson: it is the spin triplet version of the B (which has the quarks arranged in a spin singlet). The B^* has quantum numbers of 1^- (the B is 0^-) and the mass difference $m(B^*) - m(B)$ is approximately 47.5 MeV. The B^* decays 100% of the time to a B with the emission of a 47.5 MeV monochromatic photon. CUSB first observed the B^* in a scan looking for structure in the total cross section[56] (resonances above the $\Upsilon(4S)$) in 1985. It is easy to do the experiment to search for B^* production. The simplest way is to look in the inclusive photon spectrum for a bump around 50 MeV. Figure 28 shows the B^* signal in CLEO II at a center of mass energy of 10.650 GeV.

However, we don't want to just find the B^*, we want to measure the BB^* production cross section. At about 50 MeV above $2 * M_B$ one can make a BB^* pair. At 100 MeV above $2 * M_B$ one makes B^*B^* pair and BB^* production starts to fall off. CLEO is currently scanning the region above the $\Upsilon(4S)$ in 10 MeV steps, measuring the BB^* cross section at each point by counting 50 MeV photons, and will soon have a measure of the absolute cross section as a function of energy.

Who cares what the BB^* production cross section is? That brings me to the final chapter: CP violation.

B. CP Violation in the B System

We have known for 26 years that CP violation exists in the neutral kaon system. It has never been observed anywhere else. The CKM matrix offers a "natural" explanation of CP violation. It does not explain it at a fundamental level any more than the Standard Model can explain parity violation, but the theory allows for a CP violating phase in the CKM matrix in a very natural way. We want to test this standard model explanation of CP violation, and one way to do it is to observe CP violation in the B meson system. If the CKM picture is right, CP should be violated in B meson decays and although the exact magnitude is difficult to predict due to uncertainties in the values of the matrix elements, the magnitude of the effect is thought to be observable with a next generation experiment.

In Table I, I listed where B's are produced and how copiously, and from that table it is clear where one should look for CP violation: a hadron machine (Tevatron or SSC), a Z^0 factory, or an $\Upsilon(4S)$ machine. The latter two have high cross section and good signal-to-background, the former has an enormous cross section and terrible signal-to-background. Comparisons between these three options have been carried out in detail.[57] I will concentrate on the options at the $\Upsilon(4S)$.

The basic signal for CP violation in the B meson system will be the observation that the decay rate for a B to a given final state does not equal the decay

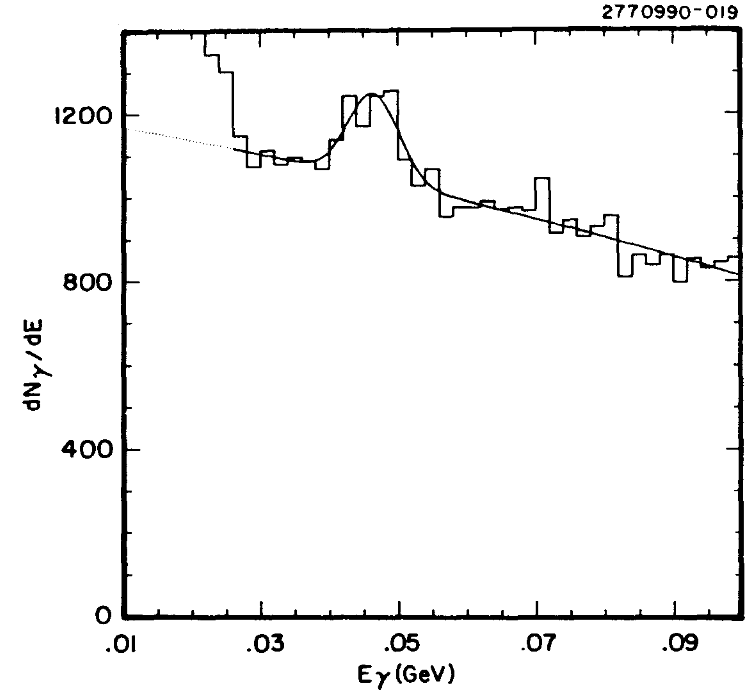

Figure 28. The inclusive photon spectrum from CLEO II at a center of mass energy of 10.65 GeV showing a bump from photons from the $B^* \to B\gamma$ transition.

rate for a $\bar{B}$ to the CP conjugate state

$$\Gamma(B \to f) \neq \bar{\Gamma}(\bar{B} \to \bar{f}).$$

The CP violation asymetry is then just

$$A^{CP} = \frac{(\Gamma - \bar{\Gamma})}{(\Gamma + \bar{\Gamma})}$$

and will be non-zero if the standard model is correct. Large CP violation asymmetries are possible in the B meson system. Asymmetries of 10% are possible in rare modes with small branching ratios ($\sim 10^{-4}$). Unfortunately in modes with large ($\sim 10^{-2}$) branching ratios, the predicted asymmetries are small ($\sim 10^{-3}$). Either way, one is going to need lots of events!

There are 3 (really 2) basic categories of experiments one can do to see CP violation in the B meson system. (A very nice description is in Karl Berkelman's SLAC lectures of 2 summers ago).[58] However, before talking about CP violation in the B's, it is useful to remember how CP violation works in the K system where it was first discovered.

In the K system there are the K^0 and $\bar{K}^0$ which are the strong interaction eigenstates of definite flavor, and K_L and K_S which are the weak interaction eigenstates of definite mass and lifetime (and they were originally thought to be eigenstates of CP). However, in 1964, the decay ,$K_L \to \pi\pi$, was observed ($K_L \to \pi\pi\pi$ if CP is conserved) with a BR of 10^{-3}, indicating that the K_L is not a CP eigenstate.

If one calls K_1 and K_2 the <u>true</u> eigenstates of CP, then the weak interaction eigenstate K_L can be written as

$$K_L = \frac{1}{\sqrt{1+\epsilon^2}}(|K_2> + \epsilon|K_1>),$$

where ϵ describes the amount of the "wrong" CP eigenstate in the weak eigenstate K_L. ϵ parameterizes what is called CP violation in the mass matrix.

So far, this is straight forward; however life may be more complicated. When $K_L \to \pi\pi$ or $K_S \to \pi\pi$ the 2 pions can be in an $I = 0$ or $I = 2$ final state, where I refers to isospin. If there is a phase difference between the two amplitudes (which the SM predicts due to the complexity of the CKM matrix) then one can get CP violation in the decay amplitudes. This is parameterized by the famous parameter ϵ' where one expects $\epsilon'/\epsilon \sim 10^{-3}$ and several very elegant experiments, NA31 at CERN and E731 at FNAL, are trying to measure this.

The B meson system, according to the SM, should also have manifestations of CP violation in the mass matrix (ϵ_B) and the decay amplitudes (ϵ'_B). But as we go to look for CP violation in the B's, there are several crucial differences. (1) CP violation is no longer much easier to see in the mass matrix (ϵ_B) than the decay amplitudes (ϵ'_B). In fact, all the plausible searches look for CP violation in the decay amplitudes. (2) Because of the extremely short lifetime of the B meson ($\sim$ 1 ps) and low production cross section, it is impractical to make beams of B mesons and the $B_L - B_S$ lifetime difference is too small to distinguish the two states by producing B mesons and allowing the B_S component to decay away. Experimentally, that is impossible. We are going to have to use other techniques. Furthermore, we will always be dealing with states of definite flavor: $B^{\pm}$, B^0, $\bar{B}^0$.

We are now going to consider 3 ways of looking for CP violation in the B meson system.

<u>CASE I</u>: CP violation in the mass matrix.

If there is CP violation, then the eigenstates of definite mass and lifetime will not be eigenstates of CP. This will result in an asymmetry in the $B^0\bar{B}^0$ mixing rate where $\Gamma(B^0 \to \bar{B}^0) \neq \Gamma(\bar{B}^0 \to B^0)$ and the rate asymmetry between these two processes will be a measure of CP violation. You will recall that mixing resulted in like sign dilepton events in our sample. CP violation will mean that there will be a difference in the number of $\ell^+\ell^+$ and $\ell^-\ell^-$ pairs in our data.

$$\begin{aligned} A &= \frac{Prob(B \to \bar{B}) - Prob(\bar{B} \to B)}{Prob(B \to \bar{B}) + Prob(\bar{B} \to B)} \\ &= \frac{N(\ell^+\ell^+) - N(\ell^-\ell^-)}{N(\ell^+\ell^+) + N(\ell^-\ell^-)} \end{aligned}$$

$$\leq 10^{-3} \; for \; the \; SM \; with \; 3 \; generations.$$ [58]

This has the great advantage of being an experiment we know how to do. Unfortunately, the small size of the asymmetry makes it prohibitive. To measure an asymmetry of 10^{-3} to 3 standard deviations requires 10^7 events. At the moment we have about 40 like sign dileptons for 250,000 $B\bar{B}$ pairs. Even with dramatic improvements in detection efficiency we will need close to 10^{10} $B\bar{B}$ pairs to establish CP violation which is unthinkable at an e^+e^- machine.

<u>CASE II</u>: CP violation in decay amplitude.

Here CP violation can be the result of the interference of two diagrams that both have the same initial and final state but different intermediate amplitudes, analogous to CP violation due to $\epsilon' \neq 0$ in the K system. For example, consider the decay $B^- \to K^- \pi^0$. There are two diagrams that can contribute to this decay: spectator $b \to u$ and a penguin. (This is illustrated in Fig. 27.) The interference between these two diagrams will cause

$$\Gamma(B^- \to K^- \pi^0) \neq \Gamma(B^+ \to K^+ \pi^0) \quad .$$

Here, the final state uniquely identifies the flavor of the B meson that decayed. Clearly the asymmetry will be largest if the two interfering amplitudes are comparable in magnitude.

I have choosen an example of a charged B decay; however this manifestation of CP violation can also occur in neutral B decays such as $\bar{B}^0 \to K^- \pi^+$ where the strangeness of the final state tags the flavor of the parent B meson. This is a straight forward way to see CP violation experimentally. It is a simple counting experiment. Predictions of the asymmetry are not very reliable but it may be as high as 10% in either $B^- \to K^- \pi^0$ or a similar mode.[58][59] Branching ratios times efficiency might be in the 10^{-5} range. The experimental upper limits are a few times that.[60] One needs, on the order of 10^8 $\Upsilon(4S)$ decays to see CP violation this way which is not an impossible goal.

Because of the simplicity of this measurement, and the likelihood that some mode will have both an appreciable asymmetry and a reasonable branching ratio, I suspect that CP violation in the B meson system will first be observed in one of these self-tagging channels. The problem is that if, for example, we accumulate 10^8 $\Upsilon(4S)$ events and don't see CP violation in $B^- \to K^- \pi^0$ or a comparable mode, we won't know if the standard model is wrong, or whether we just don't know enough about strong dynamics and final state interactions to calculate the expected rates correctly. I do not in any way wish to down play the importance of simply seeing CP violation in B decay. It would be a tremendous achievement. But because CP violation in the decay amplitude does not provide an unambiguous test of the standard model, and CP violation in the mass matrix looks reasonably hopeless, most experimentalists and theorists alike have concentrated on a third option for measuring CP violation which is experimentally less straight forward, but theoretically unambiguous.

CASE III: CP violation through mixing.

In principle, Case III is like Case II where CP violation is the result of the interference of two different amplitudes with the same initial and final state. However, in this case we let the rather large observed $B^0 \bar{B}^0$ mixing provide the alternate decay route needed for interference. Here, the fact that $\Gamma(B \to f) \neq \bar{\Gamma}(\bar{B} \to \bar{f})$ is because the interference $B^0 \to f^0$ and $B^0 \to \bar{B}^0 \to f^0$ can be of the opposite sign as the CP conjugate process. Clearly, this only works for neutral B mesons (charged B mesons don't mix) and the final states f and $\bar{f}$ must be accessible to both B^0 and $\bar{B}^0$ mesons. In the special case where the final state f is a CP eigenstate so that $f = \bar{f}$, (e.g., ψK^0_s, $\pi^+\pi^-$, K^+K^-, D^+D^-,) then the CP violating asymmetry depends only on the mixing rate and CKM matrix elements, and is independent of any strong interaction dynamics.[58] Again, CP violating asymmetries can be as large as 10% and $\epsilon Br \sim 10^{-5}$ so that one can make measurements with $\sim 10^8$ BB pairs (again, not an unreachable number). However, there are two hitches that make life complicated experimentally.

HITCH 1: Because the final state f is common to both B^0 and $\bar{B}^0$ decays, we can't tell from reconstructing the final state what the flavor of the B was that decayed; a quantity we need to know in order to form an asymmetry. We must rely on the fact that b quarks are produced in pairs of opposite flavor and if we reconstruct one b decaying to a flavor non-specific state, we must tag the second b decaying to a flavor specific state. An example is to require that the second b decay semi-leptonically and use the sign of the lepton to tag its flavor. This is the cleanest tag, although charged kaons can also be used.

HITCH 2: Both B's, the B decaying to a CP eigenstate and the B we are using to tag flavor are neutral B's and can mix. If we are doing the experiment at the $\Upsilon(4S)$, we have to consider the joint decay rate of the $B^0 \bar{B}^0$ pair which depends on the charge conjugation state, C, the pair is produced in. It is the same problem we had with mixing on the $\Upsilon(4S)$: the 2 B's have to mix coherently until one of them decays. As a result, the CP violating asymmetry is a function of the times at which the B^0 and $\bar{B}^0$ decay (t and t') and the charge conjugation state they are produced in ($C = -1$ for $\Upsilon(4S)$). We get

$$A_{C=\pm1}(t,t') = e^{-\Gamma(t+t')} 2 sin \Delta M (t \pm t') sin 2\phi$$

where $\Delta M / \Gamma$ is measured via $B^0 \bar{B}^0$ mixing at the $\Upsilon(4S)$ and ϕ is a product of CKM matrix elements and is, in fact, just the angle in the Bjorken triangle.[8] This time dependence of the asymmetry has profound consequences for a CP violation measurement at or near the $\Upsilon(4S)$ resonance.

Let us consider the effect of the time dependence of the asymmetry in a bit more detail. If we run on the $\Upsilon(4S)$, which is a natural place to do B physics since the cross section is high and the signal to background good, we produce a $B\bar{B}$ pair in a $C = -1$ state. If we try to measure the CP asymmetry by doing a simple counting experiment by counting the number of $B^0 \rightarrow \psi K_s$ and the number of $\bar{B}^0 \rightarrow \psi K_s$, we will measure identically zero. This is because, as luck would have it,

$$\int_{t=0}^{\infty}\int_{t'=0}^{\infty} dt dt' e^{-\Gamma(t+t')} sin\ \Delta M(t-t') = 0!$$

For the $B\bar{B}$ pair produced in a $C = -1$ state, we must have some information on which B, the B^0 or the $\bar{B}^0$, decayed first! Only if we can observe the times of decay, t and t', can we measure a non-zero asymmetry. If we can measure decay times and sum over all decays with a sign reversal depending on which B decayed first, it is equivalent to replacing sin $\Delta M(t-t')$ by sin $\Delta M|t-t'|$ and we get what I will call a time rectified asymmetry which is non-zero.

How can we resolve which B decayed first? At a conventional e^+e^- storage ring where the beams have equal energy (like CESR or DORIS) the B's produced at the $\Upsilon(4S)$ travel an average of about 20μm before decaying. Current vertex detector technology is not sufficient to measure such small distances, and remember, it is the difference between the decay times (or lengths) of the two B's that we need so one needs to know the production point as well. If, however, the electron and positron beams have unequal energies, E_1 and E_2, the energy in the center of mass energy can still be the $\Upsilon(4S)$ resonance, $M(\Upsilon(4S)) = \sqrt{4E_1E_2}$, but the resonance will be produced with a boost relative to the lab frame. The B's will also be boosted, and on the average will decay with a separation of $< \Delta Z >= \beta\gamma c\tau$ where $\beta\gamma$ refers to the motion of the CM. This is schematically shown in Fig. 29. For rather reasonable values of energy asymmetry one can get separations of the 2 B's by 160μm (8 on 3.5 GeV) to 220μm (9 on 3.1 GeV). Such distances are quite accessible to modern silicon vertex detector technology.[57]

Asymmetric operation of a storage ring turns out to have a host of experimental advantages. The ability to separate the decay products of the two B mesons enhances one's reconstruction ability since combinatoric backgrounds will be much reduced. Is asymmetric the only way to measure CP violation through mixing in the vicinity of the $\Upsilon(4S)$?

The answer is no. But one pays a price for staying with a conventional symmetric energy storage ring. In order to measure CP violation in, for example, ψK_s at a conventional symmetric energy machine, one cannot run on the $\Upsilon(4S)$ resonance. One must run above the $\Upsilon(4S)$ resonance where one makes a BB^* pair. When the B^* decays by emitting a photon, the $B\bar{B}$ pair is left in a $C = +1$ state, and now the asymmetry no longer integrates to zero. In fact,

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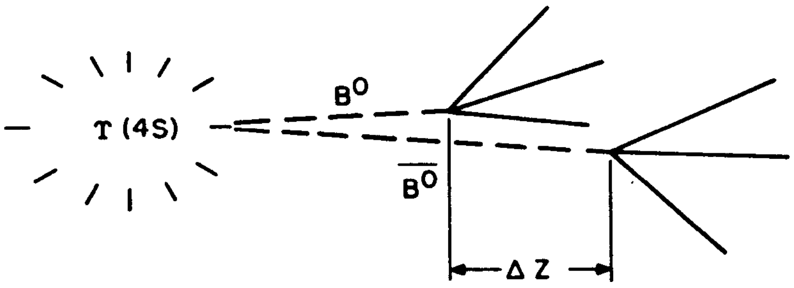

Figure 29. Diagram of asymmetric collider production of B mesons.

the integration works out so that the asymmetry is a little larger in this case. But, one has paid a price. We no longer have the advantage of the 1.2 nb of $\Upsilon(4S)$ cross section! The cross section to produce BB^* pairs above the $\Upsilon(4S)$ is not known (that is why CLEO is currently measuring it!). From energy scans above the $\Upsilon(4S)$ we know that there is an excess of .3nb above continuum in the region where BB^* should be produced. CLEO is measuring the cross section for BB^* production as a function of energy to try and determine its maximum value. Even under optimistic assumptions, one loses at least a factor of four in cross section relative to running on the $\Upsilon(4S)$ and pessimistic assumptions may be that one looses twice that.

What should one do? Build an asymmetric storage ring to measure CP violation or a symmetric one? Is either one feasible? There have been many studies that have compared luminosity requirements to measure CP violation at a symmetric machine running above the $\Upsilon(4S)$ and an asymmetric machine running on the $\Upsilon(4S)$. Perhaps the most often quoted one was done in SNOWMASS two years ago.[57] The conclusion of that and subsequent studies was that if one assumes the cross section to produce $B^0\bar{B}^{0*}$ is .14nb (mildly optimistic) then to be able to conclusively confirm or reject the standard model picture of CP violation, one has to build an asymmetric e^+e^- storage ring with a luminosity of $L = 3 * 10^{33} cm^{-2}s^{-1}$ or a symmetric e^+e^- storage ring with $L = 10^{34} cm^{-2}s^{-1}$. If the B^0B^{0*} cross section is half of what I have assumed, the symmetric option will take twice the symmetric machine luminosity. The experiments done at a symmetric or asymmetric collider are very different, and the ability to separate the B's in an asymmetric machine is a great advantage. However, the greatest advantage of the asymmetric machine is that it can utilize the full $\Upsilon(4S)$ cross section, and so one needs a lower luminosity machine. Can it be built? The machine physicists can answer that question far more competently than I can.[61] CESR holds the world's record for peak luminosity of an e^+e^- storage ring, having achieved L_{peak} of $10^{32} cm^{-2}s^{-1}$. We are talking now of machines of 30-100 times more luminosity. Can they be built? I don't know.

Will they be built and where? I, of course, don't know that either. SLAC is committed to pursuing an asymmetric B factory. Cornell, the other US contender, wants to build a machine that can operate both symmetrically and asymmetrically. No one wants to give up the advantages of asymmetry, but it is a newer and more ambitious machine design.

I think a B-factory, a machine capable of luminosities of greater than $10^{33} cm^{-2}s^{-1}$, and center of mass energies around 10 GeV will produce a wealth of information on weak decays, not just CP violation. I suspect CP violation in the B system, if it is there, will first be seen in one of the direct decays such as $B^- \rightarrow K^-\rho$ or $K^-\pi^0$. CP violation through mixing can be observed at either a symmetric or asymmetric machine, and it is up to the machine builders to tell us which they can build. Asymmetric machines haven't been built before although there is nothing to say they can't. KEK, CERN, Cornell, SLAC and DESY are all talking about B factories and it is my fervent hope that one will be built somewhere.

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