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B MESON PHYSICS WITH POLARIZED ELECTRON BEAMS AT THE SLC*

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INTRODUCTION

The expected large cross-section for $e^+e^- \rightarrow Z^\circ$ and subsequent decay to $b\bar{b}$ quarks makes the Z° an attractive place to pursue B meson physics. In addition the big Electroweak asymmetries, thought to exist in Z° decays to $b\bar{b}$ quarks with polarized electron beams, provide an outstanding handle for observation of such effects as $B^o - \bar{B}^o$ mixing. In this paper, the feasibility of such measurements is investigated and, with relatively small samples of Z°'s (a few hundred thousand), both B_d and B_s meson mixing are shown to be measurable. The subject of CP violation in neutral B mesons is discussed last, but presently such measurements seem to be out of reach.

With polarized electron beams, the experimenter can control the polarization of the Z°. Subsequently, these polarized Z°'s decay with large forward-backward asymmetries into particle-antiparticle pairs.[1] Table I gives the forward backward asymmetries A_{FB} for b quarks integrated over $-.9 < \cos\theta < .9$. The present goal of the Polarization Group working at the SLC is to deliver 45% polarized electrons[2] and, hence, should achieve a 38% A_{FB} for b quarks.

Another critical ingredient in doing B meson physics is precision vertex tracking. The machine characteristics of the SLC make possible the use of a relatively slow readout technology, and very small distances between the beams and the detectors. The SLD detector group is building a CCD chip vertex detector to be located at a radius of about 15 mm from the beam line. This device[3] provides unparallelled precision in tracking particles in all three spacial dimensions. Using this detector, it becomes possible to inclusively reconstruct B mesons with high efficiency and with a good signal to noise. The reconstruction technique is to find and identify B mesons which produce resolvable secondary vertices and decay into a charm particle which produces a resolvable tertiary vertex (see Fig. 1). Simple properties of these cascade topologies allow for the separation of B_u, B_d and B_s mesons.

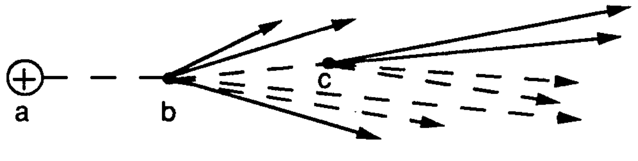

Fig. 1. A cascade B meson decay topology: (a) the primary vertex, (b) the secondary B meson decay vertex (neutral prongs are shown as dashed lines) and (c) the tertiary charmed meson decay vertex.

TABLE I. Electron beam polarization and the $\cos\theta$ integrated forward-backward asymmetry A_{FB} for b quarks.

Polarization	A_{FB} (B quarks)
0	.11
45%	.38
90%	.62

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Reconstruction of the B meson decay vertex is critical to studying B° mesons, because the amount of particle-antiparticle mixing depends on the lifetime of the meson. When the particle mixes into its antiparticle before decaying, the sign of A_{FB} is reversed. As such, when A_{FB} is plotted as a function of the B meson lifetime, it should oscillate at a frequency proportional to the mixing rate $\Delta m/\Gamma$. Data from ARGUS[4] and CLEO running at the Υ_{4s} have evidence that B_d mesons have a time integrated mixing probability about 17%. Based on this information, B_s mesons are thought to be almost completely mixed (i.e., a mixing probability of approximately 50%). If the B_s oscillation rate is large, then decay time information will be necessary to measure it.

MONTE CARLO FOR STUDYING *B* MESON MIXING

To provide "events" for studying B^o mixing, the LUND 6.3 Monte Carlo program[5] was modified to include finite particle lifetimes and B^o mixing. In Fig. 2, the B_d and B_s mixing used in the Monte Carlo are shown. In Fig. 2(a) it is seen that B_d mixing occurs on a time scale which is slow compared to the B_d meson lifetime ($\Delta m/\Gamma = .68$). As such, most of the B_d's decay before they mix, and the time integrated probability of mixing (χ) is only 17%. In Fig. 2(b), the B_s mixing rate has been set to be five times faster than the B_d rate. Here, the time integrated rate is approaching saturation (i.e., $\chi \approx 50\%$).

The Z° decay events are processed by a parametric simulation of the SLD detector. Tracks are discarded which lie outside the acceptance, track parameters are distorted appropriately according to measurement resolution and multiple scattering and, finally, a detailed simulation of particle identification in the Čerenkov Ring Image Detector is used to identify the long lived particles.

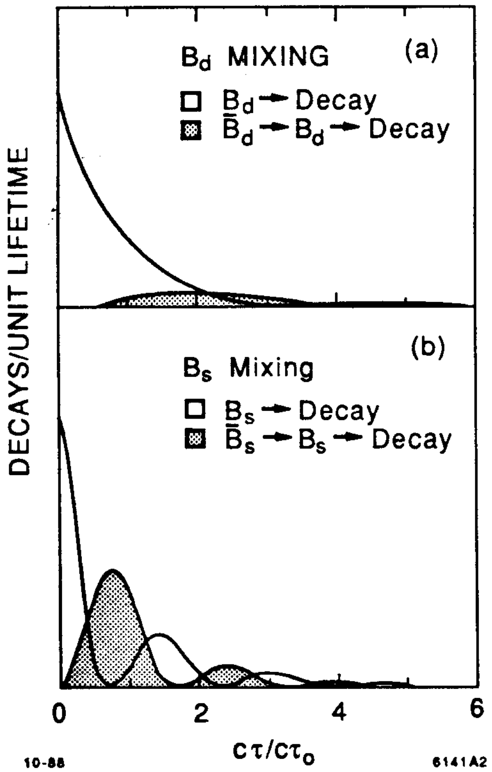

Fig. 2. Mixing probabilities versus meson lifetime for (a) B_d's and (b) B_s's.

From these processed tracks, vertex topologies are identified using simple (in concept) algorithms. The principle requirements are closeness of tracks to each other (the vertex) and the vertex's separation from the point where the beams collided. Representative cuts for closeness and separation are 45μm and 500μm, respectively.

After the initial pass to find vertices from tracks, a second pass is made where the first "track" is one of the previously found vertices. In this way, cascade topologies containing secondary and tertiary vertices are found (see Fig. 1).

The requirement that at least one cascade topology be found in an event separates $b\bar{b}$ pairs from the other events with a signal-to-noise of better than 20 to one (top quarks were not included in the simulation). As such, it wasn't deemed necessary to run the Monte Carlo with the generic mix of quarks, and only $b\bar{b}$ final states were generated. A sample of 48 K $b\bar{b}$ pairs from Z° decays with 45% polarized left-handed electrons was produced and forms the basis for the B meson mixing study.

Vertices from this process are characterized by total momentum (P_{TOT}), observed mass (M_{OBS}), charge [$Q_{b,c}$ for the secondary (b) and tertiary vertex (c)], flight path ($\gamma\beta c\tau$), and particle content (from the aforementioned particle identification system). In order to combine different B mesons with respect to lifetime, the boost factor ($\gamma\beta = P_B/M_B$) must be estimated and the flight paths corrected. A fair estimate of $\gamma\beta$ factor is found to be P_{TOT}/M_{OBS} for values of $\gamma\beta \leq 8$. Missing neutral prongs and, to a lesser extent, measurement error can cause P_{TOT}/M_{OBS} to become larger than eight and, when this occurs, the boost factor is truncated to eight.

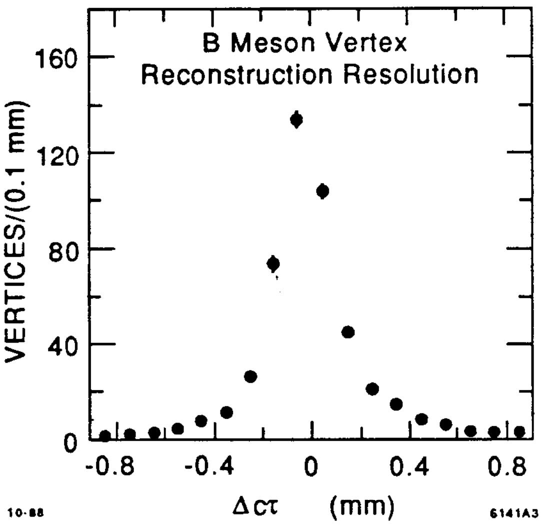

Fig. 3. B meson lifetime resolution in proper time ($c\tau$). The FWHM is 70 μm ($\sigma \sim 30$ μm) and comes mainly from uncertainty in the relativistic boost factor $\gamma\beta$.

The resulting lifetime resolution in $c\tau$ for all B mesons is shown in Fig. 3. The largest contribution to the error in $c\tau$ is from incorrect estimates of the $\gamma\beta$ boost factor. Still, the resolution predicted from this simulation is about 1/10 of a B^o lifetime and will make the observation of B_s mixing, in principle, possible up to oscillation rates of $\Delta m/\Gamma \lesssim 15$.

B_u, B_d AND B_s MESON PHYSICS

In Table II, events are separated according the charge of the secondary vertex (Q_b) and the charge of the tertiary vertex (Q_c). For each of the nine possible charge combinations, the events are broken down as to their origin: B_u, B_d, B_s and their antiparticles. Separating B_u's from neutral B's is easy: select $Q_b = \pm 1$. B^o and $\bar{B}^o$ are separated according to the sign of the tertiary vertex charge (Q_c). No effective way of using the $Q_b = Q_c = 0$ sample has yet been found.

The analysis of the B_u data is straightforward. In Fig. 4(a), the distribution of events plotted against $Q_b \cos\theta$ is shown. The large expected A_{FB} is obvious. The signal to noise for this selection is about 3.3 to one in a sample of $\sim$ 2.5 K B_u's (a 7.4% reconstruction efficiency!). The raw $A_{FB} = .34 \pm .02$

TABLE II. Breakdown of cascade topology events by secondary and tertiary vertex changes, Q_b and Q_c. For each charge combination, the sample is resolved into particles and antiparticles, as well as the meson flavors B_u, B_d and B_s (see upper left entries under $Q_b = Q_c = -1$ for key).

		Q_b Vertex					
Q_c Vertex		-1		0		+1	
		B	$\bar{B}$				
-1	u	43	2	14	23	1	22
	d	8	6	42	446	2	3
	s	2	0	22	159	0	2
0		890	21	73	82	22	899
		93	53	364	394	58	93
		23	22	141	164	27	22
+1		21	0	35	21	1	56
		3	2	492	57	7	3
		3	0	141	31	2	0

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which, upon correction for the background by a factor of $[1+(Signal/Noise)^{-1}]$, becomes

$$A_{FB}(corr) = .44 \pm .03 \ .$$

This is to be compared with the input to the Monte Carlo of .38.

In Fig. 4(b), the data from Fig. 4(a) has been binned in units of $c\tau$ for the secondary, b vertex. No apparent dependence on lifetime is present.

Separating neutral B mesons into B_d's and B_s's is harder, and information from the particle identification systems plays a crucial role. It is found that the kaon content of the tertiary vertex allows for some separation. In the Monte Carlo, b quarks fragment into B_d's 2.3 times more often then into B_s's. By requiring exactly one charged kaon to be associated with the tertiary vertex, D_s meson decays are suppressed and a signal-to-noise of 4.9 to 1 is achieved for the B_d sample. The 877 reconstructed B_d's represent a reconstruction efficiency of about 2.6%.

The B_d events are plotted against $Q_c \cos\theta$ in Fig. 5(a) and a smaller, yet clearly visible, A_{FB} is seen. The raw A_{FB} for the B_d sample is .12 ± .03. Correcting for the finite signal to noise results in $A_{FB} = .14 \pm .03$. This reduction

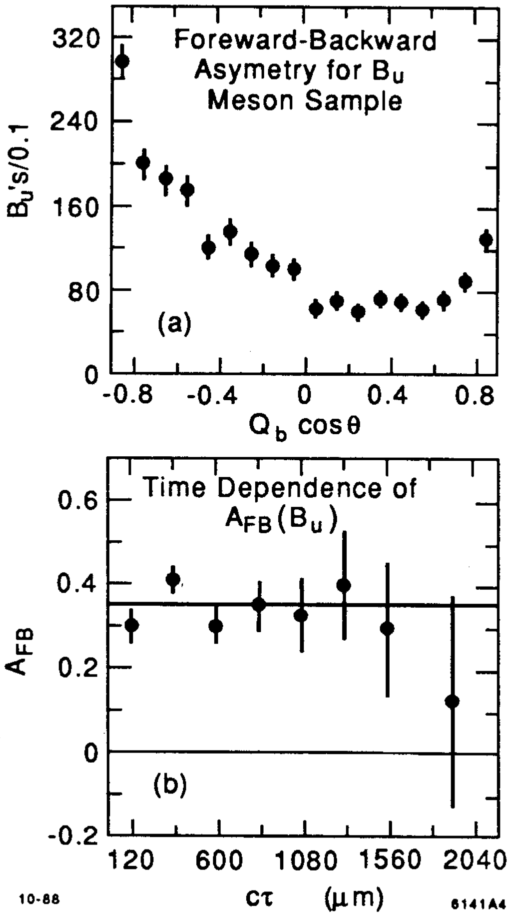

Fig. 4. A_{FB} for the B_u meson sample: (a) the time integrated sample plotted against $Q_b \cos\theta$ and (b) the data from (a) analyzed for A_{FB} and plotted versus $c\tau$ derived from the B_u meson vertex. The solid line indicates the time integrated average for the sample.

in A_{FB} for B_d mesons compared to B_u mesons can be interpreted as due to B_d meson mixing and is described by[6] $A_{FB}(obs) = A_{FB}(phys)\ (1-2\chi)$. The extent to which

$$A_{FB}(obs)/A_{FB}(phys) < 1$$

is an indication that $\chi > 0$. For the numbers produced by this Monte Carlo exercise, $\chi = .34 \pm .04$. Since the mixing phenomenon requires time to develop, the cut made in the vertex finding of flight paths greater than .5 mm introduces a substantial distortion in the measurement of χ. Simply put, by requiring a minimum flight path for the B mesons, the direct B^o decays are preferentially discarded with respect to the mixed case of $B^o \to \bar{B}^o \to$ decay. A correction for this finite lifetime requirement on vertex finding can be estimated from the Monte Carlo, and for B_d mesons is found to be .53. Applying the correction gives $\chi_{meas} = .18 \pm .02$, to be compared with the Monte Carlo input of .17

Proceeding now as for the B_u case, $A_{FB}(B_d)$ is binned in units of $c\tau$ and is shown in Fig. 5(b). We see for the first time the $B_d \to \bar{B}_d$ oscillation, directly. A fit to this data of the form

$$A_{FB} = A_{B_d} \cos(\Delta m_{B_d} t)$$

gives a $\chi^2/d.f. = 6.4/6d.f.$ The significance of the fit $(A_{B_d}/\sigma A_{B_d})$ is 4.9 and the oscillation parameter is $\Delta m_{B_d}/\Gamma_{B_d} = .65 \pm .08$. The expected number for $\Delta m_{B_d}/\Gamma_{B_d}$ is .72. The merits of this technique over the time integrated method is that systematic errors will be very small: errors in the measurement of $c\tau$ are cancelled to first order in the ratio of $\Delta m/\Gamma$ and errors in the amplitude of the effect have little bearing on the oscillation rate!

A sample of B_s mesons is extracted from the neutral B mesons by requiring the association of a pair of oppositely charged K mesons with the tertiary (charm) vertex. About half of these K pairs came from ϕ mesons and the rest are randomly distributed at higher masses. No cut is made on the K–pair mass. A sample of 116 B_s's results with a signal to noise of 1.9 to one. In Fig. 6(a),

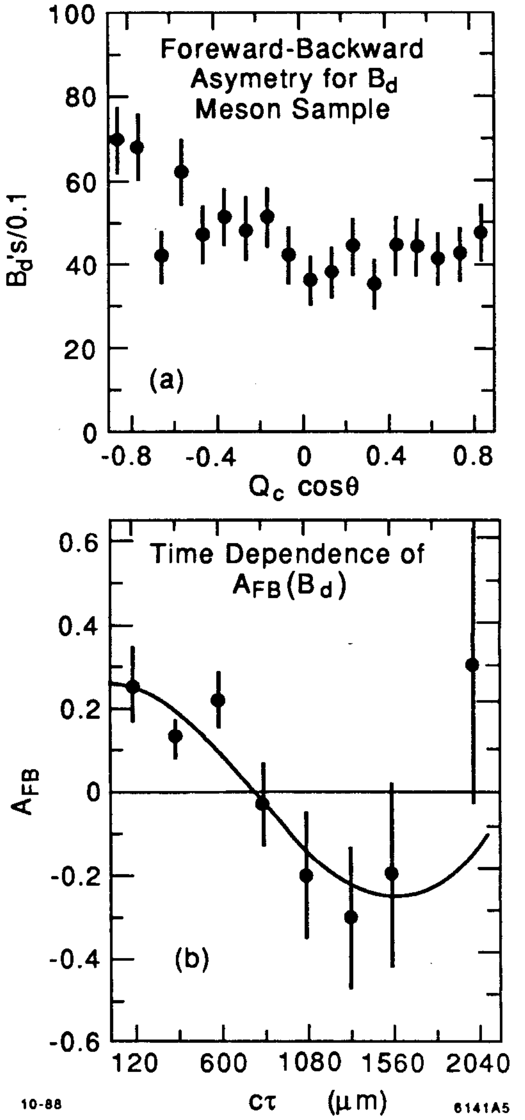

Fig. 5. A_{FB} for the B_d meson sample: (a) the time integrated sample plotted against $Q_c \cos\theta$ and (b) the data from (a) analyzed for A_{FB} and plotted versus $c\tau$ derived from the B_d meson vertex. The solid line is a fit to this data (see text).

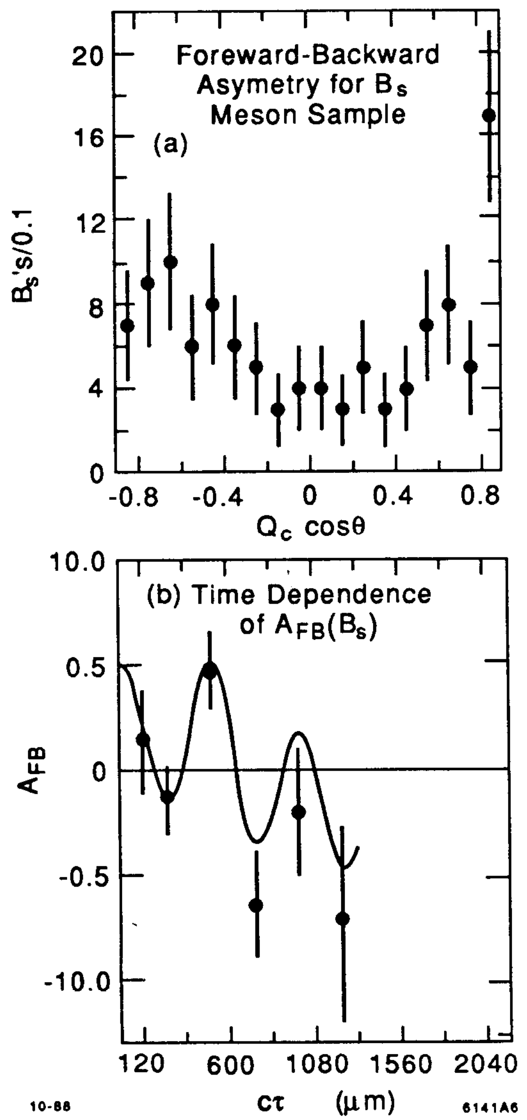

Fig. 6. A_{FB} for the B_s meson sample: (a) the time integrated sample plotted against $Q_c \cos\theta$ and (b) the data from (a) analyzed for A_{FB} and plotted versus $c\tau$ derived from the B_s meson vertex. The solid line is a fit to this data (see text).

the events are shown versus $Q_c \cos\theta$, similar to what was plotted for the B_d sample. The apparent A_{FB} is $0.\pm.09$ which, after background correction, becomes $.0\pm.14$. The mixing probability deduced from this A_{FB} is $\chi_{B_s} = .50\pm.07$. Again, the finite vertex flight path introduces a correction which is now smaller, due to the more rapid B_s oscillation rate, and is estimated to be .80 from the Monte Carlo. Hence, $\chi_{B_s}(corr) = .41 \pm .06$ to be compared to .46, the input to the Monte Carlo.

Figure 6(b) shows $A_{FB}(B_s)$ plotted versus $c\tau$. The limited number of events clearly impairs the observation of the B_s oscillation. Since the major contamination in the B_s sample are B_d's, a fit of the form

$$A_{FB} = A_{B_d} \cos(\Delta m_{B_d} t) + A_{B_s} \cos(\Delta m_{B_s} t)$$

is natural to try. The oscillation parameter Δm_{B_d} can be fixed from the prior fit to the B_d data, leaving three parameters and six data points. The $\chi^2/d.f.$ of the fit is $3.5/3 d.f.$ and the fit significance $(A_{B_s}/\sigma A_{B_s})$ is 3.3. The oscillation parameter is $\Delta m_{B_s}/\Gamma_{B_s} = 3.81 \pm .28$. The error is relatively smaller here than in the B_d case because the B_s data ranges over $\sim 2\frac{1}{2}$ periods where, in the B_d case, only half a period was fit. The ratio of $\Delta m_{B_s}/\Delta m_{B_d} = 5.9 \pm .9$ to be compared to the Monte Carlo input of 5.0 (note: $\Gamma_{B_d} = \Gamma_{B_s}$ in the Monte Carlo). Again, the systematic errors are thought to be small.

CP VIOLATION EFFECTS IN B MESONS

This section is a short summary of a previous publication.[7] CP violation is an indication of an asymmetry between the particle world and the antiparticle world. In the case of neutral B meson decay rates,

$$A_{CP} = \frac{\Gamma(B^o \to f) - \Gamma(\bar{B}^o \to \bar{f})}{\Gamma(B^o \to f) + \Gamma(\bar{B}^o \to \bar{f})} \, .$$

It is obvious that the particle-antiparticle composition of the B^o at its decay point is required. In Z° decays with polarized electron beams, this information is provided by knowing (statistically) the initial B^o meson state (from A_{FB}) and measuring how long it lives before decaying (to estimate the amount of mixing). In the case of B_d mesons, the lifetime information is helpful, but not crucial, as the time integrated mixing is only $\sim 17\%$. But for B_s mesons, where the mixing could well be $\sim 50\%$, the measurement of CP violating asymmetries will not be possible without lifetime information.

The ability of a particular technique to discern the particle-antiparticle nature of the B^o at its decay may be characterized by a "separation" asymmetry.

$$A_{sep} = \frac{N_{correct} - N_{wrong}}{N_{correct} + N_{wrong}} \, ,$$

where $N_{correct(wrong)}$ are the number of decays properly (improperly) labelled. The measured CP violation asymmetry is

$$A_{CP}(meas) = A_{CP} \cdot A_{sep} \, .$$

In the case of time integrated B_d meson decays from Z°'s, $A_{sep} = A_{FB}(B_d)$.

The number of events $N_{b\bar{b}}$ required to observe N_σ standard deviations can be expressed as

$$N_{b\bar{b}} = \frac{{N_\sigma}^2}{{A_{CP}}^2 A_{sep}^2} \, \frac{1}{2B_r(B^o \to f)} \, \frac{1}{\epsilon_f} \, \frac{1}{\epsilon_{tag}} \, \frac{1}{\sigma_{B^o}} \, ,$$

where σ_{B^o} is the probability of a b quark fragmenting to a B^o, ϵ_f is the final state reconstruction efficiency, ϵ_{tag} is the particle-antiparticle tagging efficiency, and $Br(B^\circ \rightarrow f)$ is the branching fraction to the final state f. Different methods for tagging the particle-antiparticle state can be compared by defining

$$Q_{sep} = A_{sep}{}^2 \epsilon_{tag} \; .$$

An often referred to tagging technique is to observe the charge of the lepton from b semileptonic decays. As the b quarks are produced in pairs, if a prompt lepton is observed, then the other b quark state maybe inferred. Of course, confusion with leptons emanating from the charm vertex, B_d and B_s mixing, and mis-tagging (e.g., electrons from γ's, muons from π/K decay, pions faking electrons in the calorimeter, etc.) all lead to values of A_{sep} and ϵ_{tag} less than unity.

In Table III, different tagging methods are presented. The "Gedanken Experiment" illustrates perfection. For the real world of experiments, however, Q_{sep} is found to be considerably less than one. This table shows that the polarization technique compares very favorably with direct lepton tagging.

TABLE III. Comparison of various methods to separate particle and antiparticles for B meson CP violation studies.

Method	A_{sep}	ϵ_{tag}	Q_{sep}	$N^{equiv}_{b\bar{b}}$
Gedanken Experiment	1.0	1.0	1.0	1
Lepton tag	0.50	0.12	0.03	33
FB - tag (no polarization)	0.13	0.63	0.01	100
FB - tag (45% polarization)	0.46	0.63	0.13	8
FB - tag (90% polarization)	0.75	0.63	0.35	3

The bad news is that the branching ratio estimates for prime CP violating B_d decay final states are extremely small. A general rule seems to be that the larger the expected A_{CP}, the smaller the branching ratio to that final state. Detailed estimates of required $b\bar{b}$ samples range from 3.6 x 10^7 to 3.0 x 10^8 (multiply by $\sim$ 4.5 for the number of Z° decays). This places these measurements well beyond the luminosity reach of present Z° factories.

An alternative approach to observing CP violation in $b\bar{b}$ event is to count the same sign double semileptonic decay events,

$$A_{CP}(ll) = \frac{N^{--} - N^{++}}{N^{--} + N^{++}} \; .$$

Here, one gains tremendously from the branching ratio, but the gain is more than wiped out from the expect size of A_{CP}. This double lepton signature can be compared to the case where only one lepton is observed and A_{FB} is used in place of the other lepton:

$$A_{CP}(A_{FB}) = \frac{N(l^-, backward) - N(l^+, forward)}{N(l^-, backward) + N(l^+, forward)} \; .$$

The $A_{CP}(A_{FB})$ is favored by a factor of two in the necessary event samples, due to only needing a single semileptonic decay. Still, the number of $b\bar{b}$ events will have to exceed 10^8 before the experiment is within a order of magnitude of the speculated value of A_{CP} for this inclusive lepton signal!

CONCLUSIONS

The feasibility of measuring particle-antiparticle mixing for both neutral B mesons has been demonstrated. Along with the mixing measurements, excellent determinations of B_u, B_d and B_s lifetimes will easily be made. Furthermore, the "control" sample for the B_d and B_s mixing study (i.e., the B_u sample) provides a clean measurement of A_{FB} (b quarks). The event samples necessary to pursue these studies are well within the design luminosity reach of present Z° factories.

On the other hand, studies of CP violation in B meson decay is shown to require event samples well out of reach at present. However, the argument is repeated from Ref. 7 that polarized Z°'s provide a very competitive laboratory for these studies, compared to other techniques.

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