PROSPECTS FOR THE STUDY OF B MESON DECAYS

S. Herb

Newman Laboratory of Nuclear Studies
Cornell University
Ithaca, NY 14853

Summary

Measurement of properties of the B mesons (containing b quarks) is difficult because of small production cross sections and high decay multiplicities. Possibilities for progress are discussed; detectors with very efficient $e/\mu/K$ identification and integrated e^+e^- luminosities of at least 1000 pb^{-1} will probably be necessary.

B meson decays are our only access to the weak coupling of the b quark. The hadronic part of the decay contains unique information on strong interaction dynamics, as is being shown by D meson studies. Since the B is now the heaviest known weakly decaying particle it may also give a window on 'new physics' through unusual decay modes. The first round of experiments has shown that the B properties are approximately consistent with decays through the standard charged weak current coupling, with $b\to u << b\to c$.[1] Most of the information has been deduced from inclusive lepton and hadron yields at the $\Upsilon(10.55)$ resonance (the most copious source of B mesons, with $\sigma(BB) \sim 1$ nb); B mesons have not yet been reconstructed. It is desirable to push considerably beyond the present level of experimental results. Table 1 lists some of the properties which might be measured. The difficulties are formidable and come mostly from the high multiplicities for decay of B meson pairs. This causes reduced efficiency for single particles (especially for identified particles such as electrons or kaons) and fierce combinatorial backgrounds for reconstructed final states. The CLEO group at CESR finds that the mean charged multiplicity for semileptonic decay of single B mesons is 4.1 while 6.3 for hadronic. Since the B meson pair from $\Upsilon(10.55)$ is produced almost at rest, even low multiplicity B decays are normally hidden by the decay of their twin.

Table 1

(B Meson Properties)

Standard Model, Spectator Decays	Status
$BR(B\to eX, \mu X, \tau X$ direct)	$\sim 12 + -2\%$[4]
$(b\to u)/(b\to u + b\to c)$	< 10% (model dependent)[4]
B lifetime	$< 1.4\times 10^{-12}$ sec (95% CL)[5]
B mass ($B^{\pm}$, B^{o}, B^{*}, etc.)	$2m_B < m(\Upsilon(10.55))$[1]
Hadronic Decays	
$B\to \psi K n\pi$	< 1.4% (90% CL)[4]
$B\to D n\pi$, $D^{*} n\pi$	
$B\to$ (no charmed particles)	
Non-Spectator Effects	
$B^{\pm}/B^{o}$ lifetime, semileptonic branching ratios	
$B^{\pm}\to \tau^{\pm}\nu$	
$B^{o}\overline{B}^{o}$ mixing	could be large[6]
CP violation	predicted 1^+1^- asymmetry < 1% in std. model
Standard Model Violations	
$B\to e^+e^-X$ direct (flavor changing neutral currents	< 0.9% (90% CL)
V+A quark currents	
Exotic decays ($B\to \tau e\pi$?)	

There are several possibilities for progress. One is to push as far as possible inclusive measurements, including, for example, whatever can be learned from dilepton events and lepton/kaon correlations. Another is to reconstruct B mesons in sufficient numbers that a large sample of 'random' (and unobscured) B decays is also accumulated. A third is to work at higher values of $\sqrt{s}$ so that the mesons are produced in back to back jets, using a high p_t lepton on one side as a B jet 'tag'. The purpose of this note is to briefly discuss the potential of these methods at present (100 pb^{-1}) and possible higher (1000 pb^{-1}) levels of e^+e^- luminosity.

Groups now studying B decays feel acutely the limitations of present detectors for working with high multiplicity $\Upsilon(10.55)$ decays; for example the CLEO and CUSB detectors now achieve efficiencies of 18% and 10%[3] respectively for direct electrons from B decay, resulting in percent level efficiencies for dileptons. It will be very important, and also possible to improve detectors. I will assume that this has been done and will use moderately optimistic values for detector efficiencies, for example 50% efficiency for identified electrons, $K^{\pm}$, and K^{o}_{S} can be achieved.

Inclusive Measurements

The inclusive measurements benefit from comparatively high statistics and suffer from backgrounds since, for example, electrons may come directly from B decays or indirectly from D decays, and kaons may come from $c\to s$ in D decays or from $s\overline{s}$ production. Some processes which might be studied through inclusive yields are semileptonic branching fractions (for known or unknown mixtures of $B^{\pm}$ and B^{o}), $b\to u/b\to c$, from the lepton energy spectrum, possibly corroborated by measurements of lepton-kaon correlations, and $B^{o}\overline{B}^{o}$ mixing, observed via same sign lepton pairs.

A useful exercise is to estimate dilepton yields from $B\overline{B}$ decays and to compare these with backgrounds from 'fake electrons' (pions interpreted as electrons) and from cascade electrons ($b\to DX\to eX'$). This gives for example a limit on the observability of neutral B mixing. Assumptions and results are listed in Tables II and III. $B^{o}\overline{B}^{o}$ production is taken to be 1/2 of the $\Upsilon(10.55)$ resonant cross-section, so that for complete mixing 1/4 of the lepton pairs will be the same sign. A requirement that the electron momentum be greater than 1.0 or 1.5 GeV passes most B decay electrons and rejects most D decays.

For the rather good rejection of hadrons assumed (0.002/hadron) the dominant backgrounds are direct electrons paired with fake or cascade electrons, so that only resonance events contribute to the background.

Table II

(Dilepton Signal)

Assumptions

I. 70% detector efficiency for identified electron
13% BR for $B \to eX$ (direct)
10% BR for $D \to eX$ and $B \to DX \approx 100\%$

II. 80% of B electrons have $p > 1.0$ GeV
50% of B electrons have $p > 1.5$ GeV
8% of D electrons have $p > 1.0$ GeV
1% of D electrons have $p > 1.5$ GeV

III. 1.37 charged hadrons with $p > 1.0$ GeV/$\Upsilon(10.55)$ event
0.53 charged hadrons with $p > 1.5$ GeV/$\Upsilon(10.55)$ event
0.002 probability for pion to be identified as electron

Dielectrons for $\mathcal{L} = 100\ pb^{-1}$ at $\Upsilon(10.55)$
$\approx 100{,}000\ B\bar{B}$ events:

$p > 1.0$ GeV

$e_B e_B = 10^5 \times (.13 \times .80 \times .70) \times (.13 \times .80 \times .70) = 530$

$e_B e_D = 10^5 \times 2x(.13 \times .80 \times .70) \times 2x(.10 \times .08 \times .70) = 163$

$e_B f = 10^5 \times (.13 \times .80 \times .70) \times (1.37 \times .002 \times .70) = 28$

$p > 1.5$ GeV

$e_B e_B = 10^5 \times (.13 \times .50 \times .70) \times (.13 \times .50 \times .70) = 207$

$e_B e_D = 10^5 \times 2x(.13 \times .50 \times .70) \times 2x(.10 \times .01 \times .70) = 16$

$e_B f = 10^5 \times (.13 \times .80 \times .70) \times (.53 \times .002 \times .70) = 7$

Table III

(Same Sign Dileptons)

Assumptions

I. 50% of $\Upsilon(10.55)$ cross-section is $B^o\bar{B}^o$
II. 50% of $e_B e_D$ and $e_B f$ events are same sign
III. $\alpha = 1 \equiv$ complete mixing for B^o
IV. momentum cut at $p > 1.5$ GeV

Mixing	Luminosity	Total Dileptons	Same Sign (Mixing)	(Cascade)	(fake)	Signal
α=0.25	100 pb^{-1}	230	13	8	4	13±5
α=0.10	1,000 pb^{-1}	2,300	50	80	40	50±13
α=0.05	10,000 pb^{-1}	23,000	250	800	400	250±40

The conclusion is that even if the fake electrons are reduced to a negligible level, the cascade electrons will still result in a serious contamination. If systematic uncertainties are $\lesssim$ statistical errors $\alpha = 0.10$ might be observable with 1000 pb^{-1} of luminosity. Systematic uncertainties at the 10% level and considerably more luminosity would be necessary to do better.

CP violation can be approached through same sign lepton pairs or through the total lepton asymmetry $(l^+ - l^-)/(l^+ + l^-)$ and has the advantage that contamination should not give positive effects. Using numbers from Table II gives about 200K single leptons ($e+\mu$, 50% from $B^o\bar{B}^o$), with $p > 1$ GeV from 1000 pb^{-1} at $\Upsilon(10.55)$, for a statistical accuracy of $450/100K \sim 5 \times 10^{-3}$. Observation of an asymmetry greater than $\sim .005$ is a sign that the standard 6 quark model is wrong.[6] It is hard to guess now the level of systematic uncertainties in this measurement.

B Reconstruction

Theorists have suggested $B \to \psi X \lesssim 3\%$, with much of the branching fraction at relatively small multiplicities because of the large energy absorbed by the ψ.[7] The CLEO group now has a limit of $B \to \psi X < 1.4\%$ (90% C.L.).[4] Assume for the following $B \to \psi X \sim 1\%$, giving $B \to \psi X \to$ (ee or $\mu\mu$)$X = 1.4 \times 10^{-3}$. Further assume 50% dilepton reconstruction efficiency and 20% efficiency for reconstructing B from (ee or $\mu\mu$) $K n\pi$. This gives $\sim 3 \times 10^{-4}$ as a possible attainable level for $BB \to$ reconstructed $B + X$. Better estimates for both $B \to \psi X$ and for multiplicities in the final states $B \to \psi K n\pi$ should be available from the CLEO group within the next half year on the basis of data now being taken ($0(50\ pb^{-1})$ at $\Upsilon(10.55)$ by the end of 1982).

The other prominent prospect is B reconstruction through $B \to D n\pi$ using low multiplicity decays of D (and D*) mesons. CLEO is now reconstructing D and D* mesons at $\Upsilon(10.55)$ with efficiencies of several $\times 10^{-3}$ and with modest levels of background.[8] The efficiency depends on both K identification and momentum resolution ($D^{*+} \to \pi(D^o) \to \pi K \pi$ gives a clean signal without K identification). With $K^\pm$ and K^o_S efficiencies of $\sim 50\%$ reconstruction efficiency for D's of 1-2% is possible using 2, 3, or 4 particle final states.

Typical multiplicities for $B \to D n\pi$ are $n = 4\pi^\pm + 2\pi^o$, so that n=1 or 2 branching fractions are expected to be at the $\lesssim 1\%$ level per mode.[9] These low multiplicity states are however well constrained since the D mass and momentum and the B mass and energy are (will be) known, so that combinatorial background should not be a major problem (given the reconstructed D's) and efficiency will be limited mostly by detector geometry. Assume that 5% of $B \to D n\pi$ are reconstructable with 50% efficiency. This gives a possible total rate for reconstructed B's/BB event of :

$$2B/\text{event} \times 2\% \text{ (D reconstruction)} \times 2.5\% \text{ (}Dn\pi\text{ reconstruction)} \approx 1 \times 10^{-3}$$

In summary, reconstructability of B's is not yet established but will soon be tested by the CLEO collaboration with sensitivity at the branching fractions assumed here. The success of CLEO and MARK II in reconstructing D* mesons sets a scale for the required momentum resolution. Detectors with large solid angles for charged tracking and high efficiencies for $K^\pm$ and K^o_S might achieve B reconstruction efficiencies as high as 10^{-3}, or much lower if low multiplicity decays including D or ψ mesons are very rare.

Now assume that B reconstruction efficiency of 10^{-3} is achieved at $\Upsilon(10.55)$, perhaps by an as yet unbuilt detector, giving 1000 reconstructed B's per 1000 pb^{-1} and a matching sample of 'random' unreconstructed (and uncontaminated B decays. This would permit accurate measurements of $B^o/B^\pm$ production in the vicinity of $\Upsilon(10.55)$ which together with inclusive lepton rates would give limits on the ratio of semileptonic branching fractions, as well as rates and ratios of hadronic decay modes for the reconstructed B's. A measurement of $B \to \tau\nu$, expected at the % level, would be possible, giving a definitive result for annihilation decays of the B. Searches for exotic decays at the % level would be practical. The prospect of 1000 or more reconstructed B events is therefore extremely attractive.

It is also interesting to check whether a better measurement of $B^o\bar{B}^o$ mixing could be made using these events. Assume (as in Table III) that 50% of the events are $B^o\bar{B}^o$, 1000 pb^{-1} luminosity, and $\alpha = 0.10$. Now $\alpha = 1.0$ corresponds to 1/2 of the (identified) $B^o\bar{B}^o$ events containing wrong sign leptons. This gives:

$$e(\text{wrong}) = 500 \text{ events } \times .13\times.7\times.5\times 1/2 = 1.3 \text{ electrons}$$

$$e_D = 500 \times .10\times.7\times.01 = 0.4 \text{ (all wrong sign!)}$$

$$\text{fakes} = 500 \quad .5\times(.53\times.5)\times.002\times.7 = 0.1$$

Apparently with the assumptions made this method is less sensitive than the inclusive dilepton measurement, although backgrounds are much lower, so that if backgrounds from fake electrons were several times worse it might be the superior method. A more interesting possibility would be reconstruction of both D mesons, independent of B reconstruction, at a level of say $(.02)^2 = 5\times10^{-4}$, giving 500 $D\bar{D}$ pairs per 1000 pb^{-1}. This eliminates the cascade background and could give higher sensitivity if the combinatorial background for $D\bar{D}$ is small enough.

B Jet Tagging ($\sqrt{s} \approx 30$-40 GeV)

Puhala et al.[10] estimate that requiring a lepton with $p_t > 1.2$ GeV with respect to the jet axis will give $\sim 50\%$ efficiency for $B\to\nu X$ and a B jet sample purity of $\sim 70\%$. Using both electrons and muons and assuming 50% lepton detection efficiency gives a tagging efficiency of:

$$2 \text{ B/event} \times 2 \text{ (e or } \mu) \times 13\% \; (B\to \ell X)$$

$$\times .5 \; (p_t > 1.2) \times (.5 \text{ eff}) \sim 10\% \; .$$

At $\sqrt{s} = 30$ GeV, with $\sigma_{B\bar{B}} \approx .03$ nb (1/3 unit of R), 100 pb^{-1} of data will give 300 tagged BB jets. The MAC[11] and JADE[5] detectors have isolated BB jets by this means but with lower efficiency for lepton identification and with some background due to hadron contamination of the lepton sample. The MAC group estimates that the jet sample surviving a cut at $p_t > 1$ GeV contains 40% BB, 20% DD, and 20% hadron interpreted as lepton.

For B jets with $\sqrt{s} = 30$ GeV the expected $\langle z\rangle$ for the B meson is $\langle z\rangle \sim 1\text{-}1 \text{ GeV}/M_b \approx 0.8$[12], so that the B (or B*) will have a lab rapidity of $y_{lab} \sim 1.5$. For isotropic decay of the B into massless particles this corresponds to more than 90% of the final state particles being folded into the same hemisphere — decay products of the B's in the two jets will therefore be almost completely separated, although the jets will contain some extra particles from fragmentation.

What can be done with this data sample, 300 tagged BB jets from 100 pb^{-1}, or 3000 tagged jets from 1000 pb^{-1}? It will include contamination from the DD jets as well as from the fragmentation particles within the B jets. The B content will be some mixture of $B^\pm$, B^o, B^*, B_s, etc. JADE has already placed limits on the B decay lifetime using the lepton-tagged samples[5], and limits have also been placed on dileptons from neutral current decays. Reconstruction of B mesons should be somewhat easier than at Υ(10.55) because the accompanying multiplicity is smaller ($\bar{n}_{ch} \sim 2$-3/jet from fragmentation) but much higher efficiencies will be needed and very few events per decay mode will be available. It seems unlikely that a systematic study of B decays can be made with these events but sensitivity to distinct decay modes at the % level, such as $B\to\tau\nu$, might be good.

Conclusions

I. A 'very good' detector for B decay studies should have momentum resolution $\sigma \lesssim 2\%$ at 1 GeV (the present value for CLEO), full solid angle for charged tracking, and efficiencies for identified kaons and leptons (from B decays) of about 50%, as well as rejection of hadron → lepton better than 400:1 (which may be difficult to achieve for muons). The following remarks are probably also valid for a 'fairly good' detector.

II. An integrated luminosity of 1000 pb^{-1} at Υ(10.55) could permit a significant measurement of neutral B mixing, using the inclusive dilepton signal, and a significant limit on CP violation, using both the single lepton and dilepton signals. It is not clear whether additional luminosity would be useful because modest systematic uncertainties in subtractions might then dominate the results.

III. If B reconstruction efficiencies $\sim 10^{-3}$ can be achieved at Υ(10.55) data samples of 1000 pb^{-1} will permit detailed study of the B mesons. The value of larger data samples is not obvious at present; this could change if something unusual is observed.

IV. If B reconstruction efficiencies $\sim 10^{-4}$ are achieved at Υ(10.55) study of the B decays through tagged jets will be very competitive for some special decay modes (100 pb^{-1} of luminosity could give 300 tagged jets but only 10 reconstructed B's from Υ(10.55) but will not permit thorough study of the B decays. It seems premature to invoke the arithmetic possibility of 10,000 $pb^{-1} \times 10^{-4} = 1000$ reconstructed B's.

V. Measurements of, or limits on, the branching fractions for the low multiplicity decays necessary for reconstruction of B mesons will soon be available, so that the gains from increased luminosity can be better estimated.

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