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PROPERTIES OF b-FLAVORED HADRONS*

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Abstract

Experimental progress in the study of b-flavored hadrons is reviewed. The observation of the B meson, properties of hadronic B decays, semi-leptonic B decays, and the B lifetime are discussed.

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1. Introduction

In his review of weak decays of heavy particles last year at the Paris conference, Kalmus lamented that despite considerable experimental progress in understanding B decays, several serious shortcomings persisted, namely: (1) there was no evidence for a B meson as a peak in an invariant mass plot; (2) no exclusive decay modes of the B had been identified; (3) the B lifetime was unknown. The powers that be apparently took heed, for there is new experimental information on each of these topics and exciting progress on other fronts as well. In this talk, I shall focus on four topics: the observation of the B meson; hadronic B decays; leptons in B decays; and the B lifetime. My emphasis will be on the results reported during this past year. I have specifically excluded discussion of the controversial baryon signal reported at the ISR, and deferred to R. Cashmore regarding the weak neutral current coupling of the b quark.

2. Observation of the B Meson

The CLEO collaboration working at CESR has reported[1] the observation of the B meson during the past year. Their strategy was to take data at the $\Upsilon(4S)$ resonance, where B meson production is resonantly enhanced, and search for an invariant mass peak in low multiplicity decays. They considered four decay modes (and their charge conjugates) $B^- \to D^0\pi^-$, $\bar{B}^0 \to D^0\pi^+\pi^-$, $\bar{B}^0 \to D^{*+}\pi^-$, and $B^- \to D^{*+}\pi^-\pi^-$. D^0 mesons were tagged by their $K^-\pi^+$ decays where kaons were identified by time-of-flight or dE/dx measurements. D^{*+} candidates were identified through the cascade $D^{*+} \to D^0\pi^+ \to K^-\pi^+\pi^+$. To suppress selection of charmed mesons from the continuum, the D momentum was required to be less than 2.6 GeV/c, the kinematic limit from B decay. Events were fit to each of the possible decay hypotheses after constraining the B energy to the beam energy[2] and the D^0 or D^{*+} to the appropriate mass. Lumping all the modes together produces the mass spectrum shown in Fig. 1. The statistically significant enhancement seen at 5275 MeV/c^2 is evidence for the B meson. The bump is not an artifact of the constraints of the fit, for there is no peaking in the analogous plot, Fig. 2(a), where $K^-\pi^+$ combinations outside the D^0 mass band have been substituted for "legitimate" D^0's. Figure 2(b) also shows that there is no significant structure in final states with wrong-sign combinations. The fact that low multiplicity final states

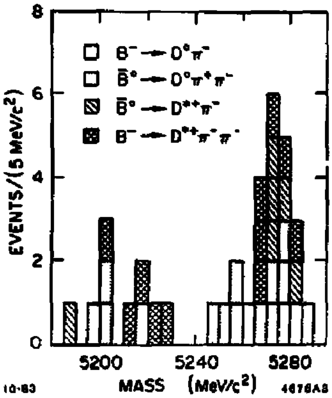

Fig. 1. Mass distribution of B meson candidates. Data from Ref. 1.

should be prominent in B decays is somewhat of a surprise, but entirely consistent with evidence on inclusive hadron production in B decays as discussed below.

To determine the B meson mass, only those decays with D^*'s are used, to avoid the possibility that a soft pion or photon was missed. The difference between the mass of the $\Upsilon(4S)$ and twice the average B meson mass is $32.4 \pm 3.0 \pm 4.0$ MeV/c^2. The neutral B mass is $5274.2 \pm 1.9 \pm 2.0$ MeV/c^2 and the charged B mass is $5270.8 \pm 2.3 \pm 2.0$ MeV/c^2. All these mass determinations depend on the production mechanism being $B\bar{B}$ and not BB^* or $B^*\bar{B}^*$. The latter two reactions would give peaks at $m_B + \Delta/2$ and $m_B + \Delta$, where $\Delta = m_{B^*} - m_B$. The CUSB collaboration sees no evidence for B^* production at the $\Upsilon(4S)$,[3] and the angular distribution of the events in the mass peak is consistent with the production of spin 0 mesons.[4] Thus the latter two reactions must be regarded as unlikely, but they are not yet excluded.

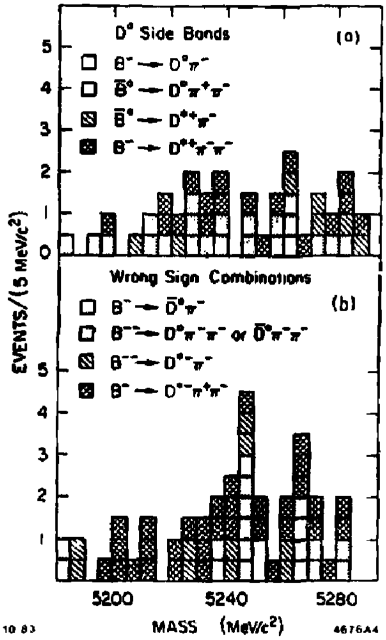

Fig. 2. Mass distribution of background B meson candidates. Data from Ref. 1.

3. Properties of Hadronic B Decays

The general properties of B decays have been studied by the CLEO and CUSB collaborations through measurements of multiplicities and particle yields at the $\Upsilon(4S)$ and the nearby continuum. The B meson contribution is isolated by subtracting an appropriately normalized continuum distribution. The B^0 and B^- populations at the $\Upsilon(4S)$ are nearly equal. Assuming the mass difference[5] is 4.4 MeV/c^2, which is consistent with their results, the CLEO collaboration finds $B(\Upsilon(4S) \to B^0\bar{B}^0) = 0.40$ and $B(\Upsilon(4S) \to B^+B^-) = 0.60$.

A. Charged and Neutral Multiplicities

The CLEO collaboration[6] has determined the average charged particle multiplicity per B decay to be $5.75 \pm .1 \pm .2$. In semi-leptonic decays it is $4.1 \pm .35 \pm .2$; and in nonleptonic decays it is $6.3 \pm .2 \pm .2$. Assuming that a D or D^* meson is always produced in the decays, the multiplicity of the non-charm hadronic component is .55 in the semi-leptonic decays and 3.8 in the nonleptonic decays. The photon multiplicity has also been measured.[7] It is $10.0 \pm .53 \pm$

.50 photons per $B\bar{B}$ event, which is roughly consistent with the expectation that charged and neutral pions are produced in the ratio 2:1. The neutral energy fraction is $0.238 \pm 0.017 \pm 0.016$ and is decidedly lower on the $\Upsilon(4S)$ than on the nearby continuum because of the neutral energy lost to neutrinos, K_L^0, and neutrons produced in B decays.

B. Particle Yields

Charged and neutral kaon yields, baryon yields, and limits on ψ production have been measured for B meson decay. The charged kaon yield is 1.94 ± 0.24 K's$/B\bar{B}$ event according to the CLEO collaboration.[8] Both the CLEO and CUSB[9] groups have measured the K^0 yields and find compatible answers: CUSB 1.58 ± 0.30 $K^0/B\bar{B}$ event, and CLEO 1.44 ± 0.24 $K^0/B\bar{B}$ event. These measurements provided early confirmation of the standard model expectation that b decays primarily to c and that the $\Upsilon(4S)$ was in fact a "B factory." Bigi predicted[10] baryon-antibaryon pairs in B decay debris at the level of a few percent. CLEO has measured[11] the branching ratio into $p\bar{p}$ (momentum above 300 MeV/c) to be $(3.4 \pm 0.6 \pm 0.9)\%$ and that into $\lambda\bar{\lambda}$ (momentum above 450 MeV/c) to be $(2.2 \pm 0.7 \pm 0.4)\%$ in agreement with prediction. Limits on $B \to \psi X$ have been set by MARK II ($< 4.9\%$ at 90% C.L.) and by CLEO ($< 1.6\%$ at 90% C.L.).[12]

C. Inclusive Hadron Spectrum

The inclusive momentum spectrum from B decays has been measured by CLEO.[13] It shows an enhancement around $x = .35$ from the semi-leptonic decays. When their contribution is subtracted, the spectrum is reminiscent of inclusive spectra in e^+e^- interactions at center-of-mass energies comparable to the B mass. Detailed fits in the high x region show evidence for two-body B decays, $B \to D\pi$, and thus confirm the existence of low multiplicity decays.

D. Inclusive Charm Production

The most significant new experimental information on hadronic B decays is the measurement of inclusive D^0 production from CLEO.[14] D^0's were identified through their $K\pi$ decay mode. Particle identification was not used, but event topology cuts which favor B decays over the continuum and cuts on the decay angles in the D^0 frame were employed. The invariant mass distribution is measured as a function of D^0 momentum, both on and off resonance, up to 2.5 GeV/c. The background from the continuum is only appreciable in the highest momentum bin (2.0-2.5 GeV/c) because the charm fragmentation function is quite hard. The subtracted spectrum is shown in Fig. 3. The momentum spectrum is surprisingly hard, nearly comparable to the D^0 spectrum in semi-leptonic B decays. The number of D^0's per B decay is measured to be $0.8 \pm 0.2 \pm 0.2$. The prominence of the D^0 signal at once confirms that the B decays primarily to charmed mesons, which rules out almost all exotic models of B decay.[15] The hard spectrum is reminiscent of the hard charm fragmentation function in e^+e^-

interactions and the apparent excess of D^0 over D^+ suggests substantial D^* production in B decay.

E. Exclusive Decay Channels

Branching ratios have been estimated[1] for two of the modes used to identify the B meson: $B(\bar{B}^0 \rightarrow D^{*+}\pi^-) = 0.026 \pm 0.019$ and $B(B^+ \rightarrow D^{*-}\pi^+\pi^+) = 0.048 \pm .030$. Analysis of the inclusive spectrum[13] shows the two-body component has a branching ratio of .015 ± .003 ± .003. Low multiplicity B decays have appreciable branching fractions, like their charm counterparts.

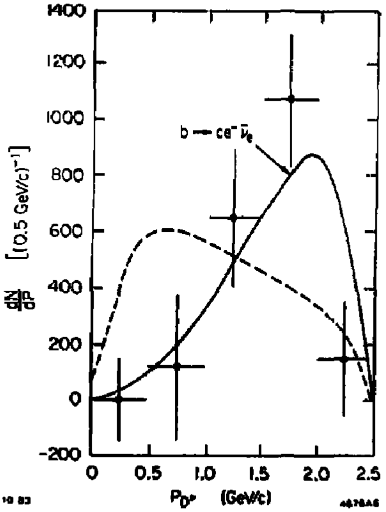

Fig. 3. D^0 momentum spectrum from B decay. Data from Ref. 14.

4. Leptons in B Decays

A. Semi – leptonic Decays at $\Upsilon(4S)$

High luminosity running at the $\Upsilon(4S)$ has resulted in refined determinations of the β decay spectrum in B decays and the semi-leptonic decay rate. Both the CLEO and CUSB experiments[16] measure the β spectrum above 1 GeV. CLEO identifies electrons by combining momentum, shower pulse height and dE/dx measurements; CUSB by measuring shower development in segmented NaI. Both experiments measure misidentification probabilities at the narrow Υ resonances. The CUSB result is shown in Fig. 4, after subtraction of electrons from continuum charm and τ decay. The observed spectrum is fit with three components:[17] $B \rightarrow D$ (or D^*) $e\bar{\nu}$; $B \rightarrow Xe\bar{\nu}$, where X is a hadron system without charm; and $B \rightarrow DX$, where $D \rightarrow e\bar{\nu}X'$. The spectral shape is well-accounted for by assuming that B mesons decay half the time into $De\bar{\nu}$ and half into $D^*e\bar{\nu}$. After correcting for the leptons below 1 GeV

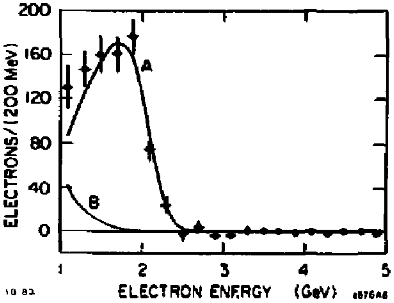

Fig. 4. Electron energy spectrum from semi-leptonic B decays. Curve A labels the $b \rightarrow ce\bar{\nu}$ contribution. Curve B the contribution from $b \rightarrow cX$, $c \rightarrow Xe\bar{\nu}$. Data from CUSB collaboration, Ref. 16.

(about 12%), CUSB finds that the semi-electronic branching ratio is 0.132 ± 0.008 ± 0.014, and CLEO finds 0.119 ± 0.007 ± 0.004. CLEO also measures the semi-muonic branching ratio to be 0.101 ± 0.005 ± 0.010. The results are in agreement with theoretical expectation[18] when hadronic enhancement factors and nonspectator contributions are taken into account. These same factors, incidentally, imply substantial differences in the semi-leptonic rates for charged and neutral B mesons. The β spectrum cuts-off sharply above 2.3 GeV/c, well below the kinematic limit for semi-leptonic decays to non-charmed mesons, indicating that final states with charm are greatly favored over those without. Using models for the expected non-charmed production,[19] both CLEO and CUSB have set upper limits on the relative branching ratio $B(b \to u)/B(b \to c)$. At the 90% confidence level, CLEO finds an upper limit of 5.0%, and CUSB an upper limit of 5.5%. These limits in turn constrain elements of the K-M matrix: $|U_{bu}| < .15\,|U_{bc}|$.

B. Semi – leptonic Decays at High Energy

Several of the experiments[20] at PEP and PETRA have determined the semi-leptonic decay rate of b-flavored hadrons by measuring the momentum and transverse momentum dependence of leptons produced in hadronic events. The transverse momentum is measured with respect to the thrust direction, which is expected to be a good measure of the original heavy hadron direction. All the analyses take the shapes of the B and D semi-leptonic lepton spectra as input, and use the distinct transverse-momentum dependence of the two spectra to separate b and c contributions. Charm mesons which have originated in B decays contribute to the inclusive lepton signal, and are included in the analyses. The results are summarized in Table I. The experiments show remarkable agreement among themselves, and are compatible with the results obtained at the $\Upsilon(4S)$. Since the high energy measurement is an average over all species of b-flavored hadrons, weighted by their production cross-sections, it is not strictly comparable to measurements at the $\Upsilon(4S)$. The analyses do convincingly demonstrate that high transverse momentum leptons tag B decays in e^+e^- interactions.

Table I

Experiment	$B(B \to e\nu X)$	$B(B \to \mu\nu X)$
CELLO	0.141 ± 0.058 ± 0.030	0.088 ± 0.034 ± 0.035
DELCO	0.128 ± 0.040 ± 0.040	
MAC	0.113 ± 0.019 ± 0.031	0.124 ± 0.018 ± 0.022
MARK II	0.135 ± 0.026 ± 0.020	0.126 ± 0.052 ± 0.030
MARK J		0.105 ± 0.015 ± 0.013
TASSO	0.136 ± 0.049 ± 0.040	0.150 ± 0.035 ± 0.035

C. Kaon – Lepton and Lepton – Lepton Correlations

CLEO has measured[21] the fraction of kaons per decay in semi-leptonic B decays at the $\Upsilon(4S)$. They find $1.00 \pm .23$ kaons/B in semi-leptonic B decays in accord with expectations if $b \rightarrow c$ transitions dominate the decays. CLEO has begun studying dilepton[16] production at the $\Upsilon(4S)$ to address several interesting topics. The overall dilepton rate is sensitive to differences in the semi-leptonic branching ratio. CLEO finds 104 ± 16 dileptons, and expects 118 if $B^o_{SL} = B^-_{SL}$. At the 90% confidence level, they constrain the ratio B^-_{SL}/B^o_{SL} to lie between 0.4 and 3.3. $B^o B^o$ mixing can lead to two identical quarks in the final state, and thus like-sign dilepton events. Constraints on the Kobayashi-Maskawa matrix elements from B lifetime measurements (see below) lead one to expect appreciable mixing, especially for B_S mesons. CLEO has measured $N(\ell^+\ell^+)/N(\ell^+\ell^-) = -0.00 \pm 0.09$, and has thus ruled out complete mixing in the B^o system at 90% C.L. Flavor changing neutral currents would in general be expected in models with no t quark at the level of $\geq 12\%$ of the semi-leptonic B decay rate.[22] CLEO has determined that the branching ratio into dileptons is less than 0.3% at the 90% confidence limit and so has eliminated these topless models. The MARK II collaboration has performed a similar analysis[23] at higher energies and finds a limit of 0.8% at 90% C.L. Significant studies of mixing, CP violation, and differences between the charged and neutral semi-leptonic branching ratios will require much larger data samples.

5. B Lifetime

The MAC and MARK II experiments at PEP have deduced the B lifetime from measurements[24] of the impact parameter of leptons at high transverse momentum with respect to the jet direction.

Method. Both experiments identified electrons and muons in e^+e^- annihilation events at 29 GeV and measured their momentum and transverse momentum (p_T) with respect to the thrust axis. MAC measures the thrust direction calorimetrically, MARK II with charged particle tracking. The MAC experiment selects leptons with $p_T > 1.5$ GeV/c for its b-enriched sample, the MARK II leptons with $p_T > 1.0$ GeV/c. Both experiments measured the distance of closest approach of the lepton trajectory to the average beam position, projected in the plane perpendicular to the beams. (The trajectory is accurately known in this plane.) The average impact parameter is proportional to $c\tau_b$, with a proportionality constant of order 1. It is calculated by Monte Carlo methods which take into account the known lepton decay spectrum, approximately-know fragmentation functions, and the event selection criteria, and is quite insensitive to uncertainties in these quantities. The last step in the analyses is to account for backgrounds, hadron misidentification and decay, and contamination from charm. These backgrounds have been evaluated in the study[20] of inclusive lepton signals, and are known quantitatively. Accordingly, there is a relation between the average measured impact parameter and the various contributions to it. For example, the MARK II experiment finds $\bar{\delta} = .20\,\bar{\delta}_{had} + .16\,\bar{\delta}_c + .64\,\bar{\delta}_b$. The average impact parameter from the hadronic background can be measured directly, and that from charm reliably calculated, so $\bar{\delta}_b$ can be deduced.

Impact Parameter Measurements. The impact parameter distribution appropriate for high p_T leptons from B decays is very sharply peaked at small impact parameter, but has a low-level tail extending well beyond its mean value. The average impact parameter is 135μ for a 10^{-12} sec lifetime, and it scales with the lifetime. The measured impact parameter distributions, shown in Figs. 5 and 6, look very different from the primordial distribution because of resolution effects. The result of convoluting a broad resolution function with the narrow impact parameter distribution is an approximately Gaussian shaped distribution displaced to the mean of the impact parameter distribution. The MAC experiment measures the weighted average of the lepton impact parameters, extracts $\bar{\delta}_b$, and converts it to a lifetime. The MARK II group fits the impact parameter distributions in both the b-enriched and c-enriched ($p_T < 1$ GeV/c) regions with separate background, charm and beauty contributions. Their fits are shown in Figs. 6(a) and 6(b).

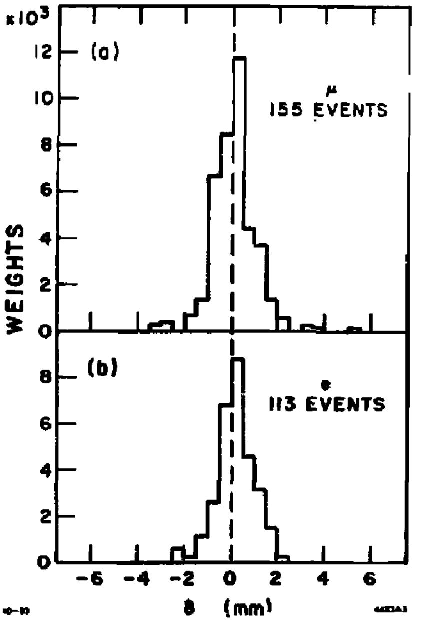

Fig. 5. Measured lepton impact parameters from MAC.

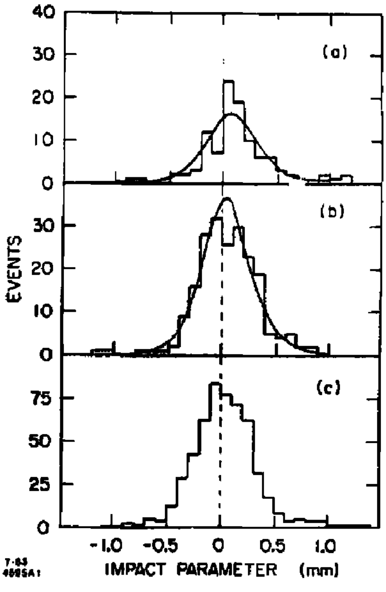

Fig. 6. Measured impact parameters from MARK II for (a) leptons in the b-enriched region; (b) leptons in the c-enriched region; and (c) hadrons in the c-enriched region.

Results. The two analyses are summarized in Table II, and are generally quite comparable in their details. It is curious that both experiments measure the average impact parameter for high p_T hadrons to be $\sim 35\mu$. This is a consistency check for the measurements because a sizable fraction of the high p_T hadrons are from b decays. The observed average impact parameter for hadrons is consistent with that expected from a picosecond beauty lifetime. Both experiments have checked their analysis techniques on Monte Carlo simulated data, and both have observed that the average electron impact parameter is approximately equal to the average muon impact parameter. In summary, the two experiments have utilized essentially identical techniques and find equivalent results. The MAC result is $\tau_b = (1.8 \pm 0.6 \pm 0.6) \times 10^{-12}$ sec and the MARK II result is $\tau_b = \left(1.20 \pm^{.45}_{.36} \pm 0.30\right) \times 10^{-12}$ sec. These results are not (quite) inconsistent with the upper limit determined by JADE,[25] $\tau_b < 1.4 \times 10^{-12}$ sec at 95% C.L.

Table II

Quantity	MAC	MARK II
p_T cut	1.5 GeV/c	1.0 GeV/c
Average Resolution	600μ	200μ
Number of Leptons	270	100
Hadron Background	20%	20%
Charm Background	13%	16%
Hadron Impact Parameter	$34 \pm 8\mu$	$36 \pm 12\mu$
Lepton Impact Parameter	$166 \pm 55\mu$	$106 \pm 29\mu$
Lifetime Determination	Weighted Average	Maximum Likelihood

Implications. Gaillard and Maiani[26] have related the B lifetime to the magnitudes of the quark mixing matrix elements U_{bc} and U_{bu}. Since $|U_{bu}| \ll |U_{bc}|$, the lifetime essentially determines $|U_{bc}| \approx 0.05$, which is considerably smaller than the analogous transition element $|U_{su}| = 0.22$. As expected, the intergenerational quark mixing is small and B decays, like K decays, are suppressed. Rather unexpected is the degree to which the decays are suppressed. In fact the smallness of the $b \rightarrow c$ transition has several interesting implications: the top quark mass is bounded from below,[27] the CP violation parameter ϵ' is of order 0.01,[28] and appreciable mixing is expected in the B_S system.[29]

6. Conclusions

Our experimental knowledge of b-flavored hadrons increased rather dramatically during the past year. The B meson has been discovered, copious charm production in B meson decay has been observed, stringent limits on $b \rightarrow u$ have been set, and the B lifetime has been measured. As exciting as these results are, it must be remembered that they derive from a very small number of experiments. The statistical significance of the B meson peak and the B lifetime work is not overwhelming, and confirmation of both effects is needed.

At face value, the picture of B decays which emerges confirms the expectations of the standard model: the $b \rightarrow c$ transition dominates and is strongly influenced by quark mixing effects. The job at hand is to measure the quark mixing parameters and test the framework Kobayashi and Maskawa established.[30] If present experimental results are confirmed, the K-M framework promises a rich phenomenology for B decays.

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