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Search for Charmless Hadronic Decays of B Mesons with the SLD Detector *

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Abstract

Based on a sample of approximately 500,000 hadronic Z^0 decays accumulated between 1993 and 1998, the SLD experiment has set limits on 24 fully charged two-body and quasi two-body exclusive charmless hadronic decays of B^+, B^0, and B_s^0 mesons. The precise tracking capabilities of the SLD detector provided for the efficient reduction of combinatoric backgrounds, yielding the most precise available limits for ten of these modes.

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The search for exclusive charmless decays of B mesons is motivated by the CKM-suppression of the W-boson mediated $b \to u$ transition, which suppresses the leading order weak decay to charmless final states by a factor of $|V_{ub}|^2/|V_{cb}|^2 \simeq 10^{-2}$ relative to that of charmed final states. Thus, observation of exclusive charmless modes with even modest branching fractions can indicate the participation of heretofore unobserved physical processes.

Recently, several results have increased interest in exclusive charmless B meson decays. The CLEO collaboration [1] has improved their measurement of the decay $B \to \eta K^*$, with the measured branching fractions $Br(B^+ \to \eta K^{*+}) = (2.73^{+0.96}_{-0.82} \pm 0.50) \times 10^{-5}$ and $Br(B^0 \to \eta K^{*0}) = (1.38^{+0.55}_{-0.44} \pm 0.17) \times 10^{-5}$ somewhat above the expected range [2] of $(0.02-0.82) \times 10^{-5}$ and $(0.01 - 0.89) \times 10^{-5}$, respectively. In addition, the DELPHI collaboration has reported a measurement [3] of the combined mode $Br(B^+ \to \rho^0\pi^+ + K^{*0}\pi^+) = (17^{+12}_{-8} \pm 2) \times 10^{-5}$, again somewhat higher than both the expected range [2] of $(0.4 - 2.0) \times 10^{-5}$ and the corresponding CLEO measurements [4] of $Br(B^+ \to \rho^0\pi^+) = (1.5^{+0.5}_{-0.5} \pm 0.4) \times 10^{-5}$ and $Br(B^+ \to K^{*0}\pi^+) < 2.7 \times 10^{-5}$.

In this Letter, we present limits from the SLD detector on several two, three, and four-prong fully charged two-body and quasi-two-body final states. Although the B meson sample available to the SLD detector is fairly limited in comparison to those produced at LEP, CESR, and the TEVATRON, the excellent tracking and *a priori* knowledge of the B meson production point admit limits competitive with those produced elsewhere. Most limits presented here on four-prong final states, for which combinatoric backgrounds are worst, are the first available. In addition, the cms energy available to experiments running at the Z^0 pole allows the study of B_s decays, which are inaccessible to experiments running at the $\Upsilon(4S)$.

Search modes reported in this Letter include $B^0, B^0_s \to P^+P^-$ (two-prong), $B^+ \to P^+V^0$ (three-prong), and $B^0, B^0_s \to V^0V^0$ (four-prong), and their charge-conjugates, where $P = \pi, K$ is a stable pseudoscalar meson and $V = \rho^0, K^{*0}, \phi$ is a vector meson resonance with a sizeable branching fraction into two charged pseudoscalar mesons (100%, 66.7%, and (49.1

$\pm$ 0.8)% [5], respectively). The ability to fully reconstruct the decaying B meson state, with precise momentum and vertex information for each of the charged daughter tracks, provides an essential constraint in the analysis; no attempt was made to search for modes with one or more long-lived final state neutral particles.

The SLD detector [6] instruments the sole interaction region of the SLAC Linear Collider (SLC). The luminous region of the SLC is an ellipsoid of dimensions approximately 2 and 0.8 μm in the horizontal (x) and vertical (y) directions perpendicular to the beam axis, and 700 μm along the beam axis. Due to motion of the collision point, however, the location of the luminous region is known to only $\sim 7\mu m$ in x and y.

Charged particle tracks are reconstructed in the central drift chamber (CDC) and the CCD-based pixel vertex detector (VXD) in a uniform axial magnetic field of 0.6T. Including the uncertainty in the location of the luminous region (IP) of the SLC, the VXD2 vertex detector, in place through 1995, exhibited an $r-\phi$ ($r-z$) impact parameter resolution of $11\mu m$ ($38\mu m$) at high momentum, and $71\mu m$ ($80\mu m$) at $p_\perp\sqrt{\sin\theta} = 1.0$ GeV/c [7]. The corresponding resolution for the VXD3 vertex detector, in place since 1996, is $8\mu m$ ($10\mu m$) at high momentum, and $34\mu m$ ($35\mu m$) at $p_\perp\sqrt{\sin\theta} = 1.0$ GeV/c. The combined CDC/VXD momentum resolution in the plane perpendicular to the beam axis is $\delta p_\perp/p_\perp = \sqrt{(.01)^2 + (.0026 p_\perp/\mathrm{GeV/c})^2}$. High momentum charged tracks are reconstructed in the range $|\cos\theta| < 0.85$, with an efficiency of 96% for $|\cos\theta| < 0.65$. A segmented Si-W forward calorimeter, with polar angle acceptance between 23 mr and 68 mr, is used to monitor the SLC luminosity via t-channel Bhabha scattering.

The SLD accumulated an integrated luminosity of 19.1 pb^{-1} of e^+e^- annihilation data at the Z^0 pole between 1993 and 1998. Of this, 14.0 pb^{-1} was taken with the upgraded VXD3 vertex detector in place.

The complete reconstruction of the fully-charged final state provides a number of constraints which can be used to discriminate between signal and potential background sources. Candidate track combinations must be consistent with having arisen from a single vertex. This vertex is displaced from the collision point by an average of $\sim$3mm, which is measured

with an average uncertainty of 60μm for the search modes. The point of closest approach of the extrapolated vertex momentum resultant to the SLD IP ('vertex impact parameter') must be consistent with zero. The invariant mass of the tracks forming the vertex must be consistent with that of the B meson and have a total momentum consistent with known fragmentation properties. Tracks emerging from the B-meson decay vertex should have a relatively small opening angle, a large momentum, and a relatively large impact parameter with respect to the SLD IP. For quasi two-body modes involving vector meson resonances ($B \to PV$ and $B \to VV$), two of the charged tracks must have an invariant mass consistent with that of each resonance. In addition, for $B \to PV$ modes, the decay angle θ_h of the V state with respect to its flight direction ('helicity angle') must be consistent with the distribution $d\Gamma/d\Omega_h \propto \cos\theta_h$ dictated by angular momentum conservation.

Candidate decays were reconstructed by considering all combinations of two, three, and four tracks which pass track quality cuts [6] and with total charge 0 for PP and VV candidates, and ± 1 for PV candidates. The invariant mass of the candidate decay was required to be above 5.05 GeV/c^2 (5.15 GeV/c^2) for B^+ and B^0 (B_s^0) modes. The probability of the vertex fit to the candidate tracks was required to be greater than 1.0% (0.5% for $B \to VV$ modes and $B \to PV$ with $V = \phi$), with a significance (separation from the SLD IP divided by the associated error) of greater than 1.0 (0.6 for $B \to VV$ modes and $B \to PV$ with $V = \phi$). The smallest impact parameter D, normalized to its corresponding uncertainty, of any track in the candidate vertex was required to be greater than 1.1 (0.6 for $B \to VV$ modes and $B \to PV$ modes with $V = \phi$). The change in the vertex invariant mass between the assumption of the nominal (kaon) mass and pion mass for all relevant tracks in the candidate vertex was required to be less than 0.3 GeV/c^2 (1.2 GeV/c^2) for the $B \to PK^{\pm}$ ($B \to K\rho^0$) modes; this cut suppresses background vertices which get an artificially large mass due to a mistaken mass hypothesis for one or more tracks. A second mass reconstruction quantity $\mathcal{M}_{VV}$, defined to be the sum of the absolute values of the differences between the reconstructed and nominal masses of the vector meson and B meson candidates, was required to be less than 0.6 GeV/c^2, 0.4 GeV/c^2, and 0.4 GeV/c^2 for the $B \to \rho^0\rho^0$, $B \to \rho^0 V$ ($V \neq \rho^0$),

and $B_s^0 \to \bar{K}^{*0} K^{*0}$modes, respectively. For relevant modes, the reconstructed vector meson masses were required to be in the ranges $[0.2 - 1.1]$, $[0.7 - 1.0]$, and $[1.000 - 1.035]$ GeV/c^2 for $V = \rho^0$, K^{*0}, and ϕ. Finally, $|\cos\theta_h|$ was required to be greater than 0.3 for $B \to PV$ modes.

To further suppress background, an *ad-hoc* discriminator function was devised, and tuned to a sample of Monte Carlo (MC) $Z^0 \to b\bar{b}$ events approximately ten times that of data, and a sample of light quark (udsc) events approximately four times that of data. For $B \to PP$ modes, this function took the form

$$\mathcal{F}_{PP} = a_0 e^{-\frac{(m-M_b)^2}{2(\delta m)^2}} - a_1 e^{\frac{-m}{m_0}} - a_2 e^{-\frac{S}{3}} - a_3 e^{-\tilde{\lambda}} + a_4 e^{-\frac{\lambda}{0.3}} - a_5 e^{-\frac{P}{0.03}} - a_6 e^{-\frac{D}{3}} - a_7 e^{-\frac{\tilde{I}}{\tilde{I}_0}} + a_8 e^{-\frac{I}{I_0}} - a_9 e^{-\frac{X}{0.5}} + a_{10} e^{-\frac{\Delta M}{0.2\mathrm{GeV}}},$$

with m the invariant mass of the candidate vertex, S the vertex significance, λ the largest angle between any tracks belonging to the vertex ($\tilde{\lambda} = 1/\lambda - 0.9$), P the vertex fit probability, D the minimum normalized impact parameter, I the vertex impact parameter ($\tilde{I} \times 1000 + 24 = 1/(I + 0.001)$), and $X = E_{vert}/E_{beam}$ the scaled vertex energy. ΔM is the difference in the vertex mass between the pion and kaon hypotheses, and exploits the propensity for all tracks deriving from decays of the various search modes to be at high momentum. The parameters $a_i > 0$, m_0, I_0, and $\tilde{I}_0$ were tuned separately for the individual search modes, while M_b was set to 5.28 GeV/c^2 for B^0 or B^+ and 5.37 GeV/c^2 for B_s.

For $B \to PV$ modes, the discriminator function took the form

$$\mathcal{F}_{PV} = \mathcal{F}_{\mathcal{P}\mathcal{P}}\big|_{a_{10}=0} + a_{11} e^{-\frac{(m_v - M_v)^2}{2(\delta m_v)^2}} + (1 - \cos(h\pi)),$$

with m_v the invariant mass of the vector meson candidate, and $h = \cos\theta_h$. The vector meson masses M_v were set to 0.77, 0.89 and 1.02 GeV/c^2 for ρ, K^{*0} and ϕ candidates, respectively, with corresponding widths δm_v of 0.1, 0.08 and 0.006 GeV/c^2, respectively.

For $B \to VV$ modes, the discriminator function took the form

$$\mathcal{F}_{VV} = \mathcal{F}_{\mathcal{P}\mathcal{P}}\big|_{a_{10}=0} + a_{11} e^{-\frac{(m_v^{(1)} - M_v^{(1)})^2}{2(\delta m_v^{(1)})^2}} + a_{12} e^{-\frac{(m_v^{(2)} - M_v^{(2)})^2}{2(\delta m_v^{(2)})^2}} + a_{13} e^{-\frac{\mathcal{M}_{VV}}{0.4\mathrm{GeV}}},$$

with vector meson candidates selected according to the track partition yielding vector meson masses closest to those of the search mode.

The discriminator functions were tuned for the various search modes by maximizing the separation between the SLD MC sample (which contains no charmless B hadron decays) and separately generated MC samples representing each individual search mode. The signal region for each search mode was then defined according to a cut on the output of the corresponding discriminator function. For each search mode, the value of this cut was selected in an unbiased way by minimizing the average expected MC Poisson upper limit $\mathcal{P}$ according to

$$\mathcal{P} = \sum_{i=0}^{\infty} P(u,i) Br_i(\varepsilon)$$

where $P(u,i)$ is the Poisson probability for finding i background events given an expectation of u, and $Br_i(\varepsilon)$ is the 90% CL upper limit for the branching ratio if i events are found. The expected signal efficiency from the MC simulation at these optimal points ranged between 24.8% and 37.9% for the various search modes, with expected backgrounds of between 0.0 and 0.48 events. The efficiency is that for all B meson signal events, regardless of whether the decay occurred in the fiducial region of the detector, but does not take into account the branching ratios into fully-charged two-body final states for the vector mesons in the $B \to PV$ and $B \to VV$ modes.

The signal efficiencies were determined from the SLD MC simulation, and thus are subject to modeling uncertainties. The efficiency of the SLD tracking system was constrained by studying the track multiplicity distributions of inclusively tagged $Z^0 \to b\bar{b}$ events, which are identified with approximately 98% purity by the SLD [8]. The kinematic distributions of tracks from such events are well constrained by measurements of B meson decay at the $\Upsilon(4S)$ [9], as well as measurements of heavy-quark associated multiplicity at the Z^0 pole [10]. The resulting comparison of the momentum dependence of the multiplicity between inclusively tagged MC and data events indicated a deficit of $\sim 5\%$ in the tracking efficiency below 1.5 (0.8) GeV/c for the VXD2 (VXD3) data sample, leading to a reduction in the estimated

signal mode efficiency of $\delta\varepsilon/\varepsilon \simeq 1-2\%$.

The momentum resolution at high momentum was studied by comparing the width of the reconstructed mass peak between data and MC for a sample of exclusively reconstructed $D^+ \to K^-\pi^+\pi^+$ decays. To account for the somewhat larger width observed in data, the MC momentum distribution was smeared according to $1/p_\perp \to 1/p_\perp$ + Gaussian, for a Gaussian width of 0.002 (0.001) $(\mathrm{GeV/c})^{-1}$ for the VXD2 (VXD3) data sample. The resulting change in the MC mass width, for example for the $B^+ \to \rho^0\pi^+$ search mode, is from 146 to 184 $\mathrm{MeV/c^2}$ for the VXD2 data sample. The resulting efficiency loss varied between $\delta\varepsilon/\varepsilon \simeq 2-5\%$. Smearing of the radial and longitudinal track origin parameters, constrained by comparisons of $r-\phi$ and $r-z$ impact parameter distributions between data and MC, yielded an additional efficiency loss of $\delta\varepsilon/\varepsilon \simeq 2-4\%$. As a cross check, after the inclusion of the above corrections in the MC efficiency calculation, the number of reconstructed $D^+ \to K^-\pi^+\pi^+$ decays is within 3% of the MC expectation, well within the experimental uncertainty on the $D^+ \to K^-\pi^+\pi^+$ branching fraction and the D^+ production rate.

Application of the various search mode selection algorithms to the full 1993-8 SLD data sample yielded a total of four distinct candidate events (E_1 – E_4) which populated the signal regions of six separate search modes. The events observed (background expected) in each of these modes were as follows: event E_1 for $B^0 \to \rho^0\rho^0$ (0.31); events E_1, E_2 for $B^0 \to \overline{K}^{*0}\rho^0$ (0.49); events E_1, E_2, E_3 for $B^0 \to \overline{K}^{*0}K^{*0}$(0.27); event E_4 for $B^0 \to \phi\overline{K}^{*0}$(0.14); event E_1 for $B_s^0 \to \overline{K}^{*0}\rho^0$(0.34); and events E_1, E_3 for $B^0 \to \overline{K}^{*0}K^{*0}$(0.17). For the remaining search modes, no events were seen.

The mode for which the observed signal was least likely to be accounted for by a statistical fluctuation in the expected background was $B^0 \to \overline{K}^{*0}K^{*0}$. The Poisson likelihood of an expected background of 0.27 events fluctuating to three or more events is 0.27%, but depends strongly on the value of the expected background. A study in which additional background was admitted into the signal region by loosening the discriminator function cut yielded an additional 11 events in this mode, compared to a MC expectation of an additional 3 events

(the agreement was satisfactory for other modes). Thus, for this mode there is reason to believe that the background is underestimated, and so, as for other modes, only an upper limit will be quoted.

The branching ratio upper limits L are related to the statistical upper limits α on the number of observed events according to $\alpha = S \cdot L; \quad S = N_B \cdot \varepsilon$, with N_B the estimated number of applicable B meson decays, and ε the estimated efficiency for reconstructing the given signal mode. The number of $B^+(B^0)$ and B_s^0 meson decays in the full SLD data sample is estimated from the measured SLD sample luminosity and known B meson production rates to be $(1.02 \pm 0.05) \times 10^5$ and $(0.27 \pm 0.05) \times 10^5$, respectively. It has been assumed that $(21.7 \pm 0.1)\%$ of hadronic Z^0 decays involve primary b quarks, and of these, $(39.7^{+1.8}_{-2.2})\%$ are B^0 or B^+ decays, and $(10.5^{+1.8}_{-2.2})\%$ are B_s^0 decays [5]. The uncertainty in the signal mode efficiencies was conservatively estimated to be the total difference in the MC efficiency estimate with and without the extra momentum, tracking efficiency, and track origin parameter smearing. Including an additional MC statistical error of $\delta\varepsilon/\varepsilon \simeq 2-5\%$, due to the limited size of the generated signal mode samples, the total modeling error was between 6 – 10% for all modes.

Table 1 exhibits the number of candidate events, expected background, efficiency, sensitivity (S), and resulting 90% CL upper limits for both the Bayesian [11] and Classical [12] approaches for the 24 search modes. Each four-prong mode limit presented here, with the exception of $B^0 \to \phi\overline{K}^{*0}$ and $B^0 \to \phi\phi$, either improves upon the existing limit [5], or is the first available limit for the given mode. Two of the two-prong B_s^0 modes ($\pi^+\pi^-$ and $K^-\pi^+$) are competitive with existing limits [5]. Furthermore, the DELPHI result

$$BR(B^+ \to \rho^0\pi^+, K^{*0}\pi^+) = (1.7^{+1.2}_{-0.8} \pm 0.2) \times 10^{-4}$$

is ruled out at 90% CL by the corresponding SLD limits.

In conclusion, the excellent tracking capabilities of the SLD detector have enabled the SLD to establish a number of unique or competitive limits on the decay of B mesons to exclusive charmless final states. In particular, most of the four-prong quasi two-body lim-

its presented here are the most stringent limits available. In addition, the SLD limits of $BR(B^+ \to \rho^0\pi^+) < 0.83 \times 10^{-4}$ and $BR(B^+ \to K^{*0}\pi^+) < 1.19 \times 10^{-4}$ (90% CL) rule out a DELPHI observation of the sum of these two modes [3] in favor of more stringent limits from CLEO [4].

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TABLES

Mode	ε	S ($\times 10^{-4}$)	Bckd	Data	UL (B; $\times 10^4$)	UL (C ; $\times 10^4$)
$B^0 \to \pi^+\pi^-$	.338	$3.46 \pm .31$	0.03	0	0.69	0.67
$B^0 \to K^-\pi^+$	.345	$3.53 \pm .32$	0.14	0	0.67	0.66
$B^0 \to K^+K^-$	.341	$3.49 \pm .28$	0.14	0	0.67	0.66
$B_s^0 \to \pi^+\pi^-$	.379	$1.02 \pm .16$	0.03	0	2.35	2.32
$B_s^0 \to K^-\pi^+$	.335	$0.91 \pm .15$	0.10	0	2.62	2.61
$B_s^0 \to K^+K^-$	.311	$0.84 \pm .14$	0.20	0	2.77	2.83
$B^+ \to \rho^0\pi^+$	.272	$2.78 \pm .26$	0.34	0	0.81	0.83
$B^+ \to \rho^0K^+$	.264	$2.70 \pm .24$	0.41	0	0.83	0.86
$B^+ \to K^{*0}\pi^+$	.285	$1.94 \pm .17$	0.17	0	1.21	1.19
$B^+ \to K^{*0}K^+$	.248	$1.69 \pm .18$	0.17	0	1.39	1.38
$B^+ \to \phi\pi^+$	.301	$1.51 \pm .12$	0.07	0	1.59	1.53
$B^+ \to \phi K^+$	.321	$1.61 \pm .12$	0.14	0	1.47	1.44
$B^0 \to \rho^0\rho^0$	.270	$2.76 \pm .24$	0.31	1	1.53	1.33
$B^0 \to \bar{K}^{*0}\rho^0$	.259	$1.76 \pm .15$	0.49	2	3.22	2.79
$B^0 \to \bar{K}^{*0}K^{*0}$	.312	$1.42 \pm .12$	0.27	3	5.14	4.58
$B^0 \to \phi\rho^0$	.305	$1.53 \pm .13$	0.14	0	1.54	1.52
$B^0 \to \phi\bar{K}^{*0}$	.302	$1.01 \pm .08$	0.14	1	4.23	3.75
$B^0 \to \phi\phi$	.300	$0.74 \pm .05$	0.00	0	3.29	3.13
$B_s^0 \to \rho^0\rho^0$	.284	$0.77 \pm .13$	0.27	0	2.99	3.12
$B_s^0 \to \bar{K}^{*0}\rho^0$	.279	$0.50 \pm .09$	0.34	1	8.31	7.48
$B_s^0 \to \bar{K}^{*0}K^{*0}$	.272	$0.33 \pm .05$	0.17	2	17.77	16.40
$B_s^0 \to \phi\rho^0$	.297	$0.39 \pm .06$	0.07	0	6.09	6.02
$B_s^0 \to \phi K^{*0}$	.272	$0.24 \pm .04$	0.14	0	9.78	9.88
$B_s^0 \to \phi\phi$	.316	$0.21 \pm .03$	0.00	0	11.81	11.54

TABLE I. Summary of efficiency (ε), sensitivity (S), expected background, number of events in the signal region, Classical (C) and Bayesian (B) 90% CL Upper Limit for the 24 search modes. Note that the sensitivities (but not the efficiencies) take account of the branching fraction for ϕ or K^{*0} into a fully-charged two body final state, where applicable.