Search for Charmless $B \to VV$ Decays

R. Godang,[1] G. Bonvicini,[2] D. Cinabro,[2] M. Dubrovin,[2] S. McGee,[2] G. J. Zhou,[2] A. Bornheim,[3] E. Lipeles,[3] S. P. Pappas,[3] M. Schmidtler,[3] A. Shapiro,[3] W. M. Sun,[3] A. J. Weinstein,[3] D. E. Jaffe,[4] G. Masek,[4] H. P. Paar,[4] D. M. Asner,[5] A. Eppich,[5] T. S. Hill,[5] R. J. Morrison,[5] R. A. Briere,[6] G. P. Chen,[6] T. Ferguson,[6] H. Vogel,[6] A. Gritsan,[7] J. P. Alexander,[8] R. Baker,[8] C. Bebek,[8] B. E. Berger,[8] K. Berkelman,[8] F. Blanc,[8] V. Boisvert,[8] D. G. Cassel,[8] P. S. Drell,[8] J. E. Duboscq,[8] K. M. Ecklund,[8] R. Ehrlich,[8] A. D. Foland,[8] P. Gaidarev,[8] L. Gibbons,[8] B. Gittelman,[8] S. W. Gray,[8] D. L. Hartill,[8] B. K. Heltsley,[8] P. I. Hopman,[8] L. Hsu,[8] C. D. Jones,[8] J. Kandaswamy,[8] D. L. Kreinick,[8] M. Lohner,[8] A. Magerkurth,[8] T. O. Meyer,[8] N. B. Mistry,[8] E. Nordberg,[8] M. Palmer,[8] J. R. Patterson,[8] D. Peterson,[8] D. Riley,[8] A. Romano,[8] J. G. Thayer,[8] D. Urner,[8] B. Valant-Spaight,[8] G. Viehhauser,[8] A. Warburton,[8] P. Avery,[9] C. Prescott,[9] A. I. Rubiera,[9] H. Stoeck,[9] J. Yelton,[9] G. Brandenburg,[10] A. Ershov,[10] D. Y.-J. Kim,[10] R. Wilson,[10] T. Bergfeld,[11] B. I. Eisenstein,[11] J. Ernst,[11] G. E. Gladding,[11] G. D. Gollin,[11] R. M. Hans,[11] E. Johnson,[11] I. Karliner,[11] M. A. Marsh,[11] C. Plager,[11] C. Sedlack,[11] M. Selen,[11] J. J. Thaler,[11] J. Williams,[11] K. W. Edwards,[12] R. Janicek,[13] P. M. Patel,[13] A. J. Sadoff,[14] R. Ammar,[15] A. Bean,[15] D. Besson,[15] X. Zhao,[15] S. Anderson,[16] V. V. Frolov,[16] Y. Kubota,[16] S. J. Lee,[16] R. Mahapatra,[16] J. J. O'Neill,[16] R. Poling,[16] T. Riehle,[16] A. Smith,[16] C. J. Stepaniak,[16] J. Urheim,[16] S. Ahmed,[17] M. S. Alam,[17] S. B. Athar,[17] L. Jian,[17] L. Ling,[17] M. Saleem,[17] S. Timm,[17] F. Wappler,[17] A. Anastassov,[18] E. Eckhart,[18] K. K. Gan,[18] C. Gwon,[18] T. Hart,[18] K. Honscheid,[18] D. Hufnagel,[18] H. Kagan,[18] R. Kass,[18] T. K. Pedlar,[18] H. Schwarthoff,[18] J. B. Thayer,[18] E. von Toerne,[18] M. M. Zoeller,[18] S. J. Richichi,[19] H. Severini,[19] P. Skubic,[19] A. Undrus,[19] V. Savinov,[20] S. Chen,[21] J. Fast,[21] J. W. Hinson,[21] J. Lee,[21] D. H. Miller,[21] V. Pavlunin,[21] E. I. Shibata,[21] I. P. J. Shipsey,[2,1] D. Cronin-Hennessy,[22] A. L. Lyon,[22] E. H. Thorndike,[22] T. E. Coan,[23] V. Fadeyev,[23] Y. S. Gao,[23] Y. Maravin,[23] I. Narsky,[23] R. Stroynowski,[23] J. Ye,[23] T. Wlodek,[23] M. Artuso,[24] R. Ayad,[24] C. Boulahouache,[24] K. Bukin,[24] E. Dambasuren,[24] G. Majumder,[24] G. C. Moneti,[24] R. Mountain,[24] S. Schuh,[24] T. Skwarnicki,[24] S. Stone,[24] J. C. Wang,[24] A. Wolf,[24] J. Wu,[24] S. Kopp,[25] M. Kostin,[25] A. H. Mahmood,[26] S. E. Csorna,[27] I. Danko,[27] K. W. McLean,[27] and Z. Xu[27]

(CLEO Collaboration)

[1]*Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061*
[2]*Wayne State University, Detroit, Michigan 48202*
[3]*California Institute of Technology, Pasadena, California 91125*
[4]*University of California, San Diego, La Jolla, California 92093*
[5]*University of California, Santa Barbara, California 93106*
[6]*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213*
[7]*University of Colorado, Boulder, Colorado 80309-0390*
[8]*Cornell University, Ithaca, New York 14853*
[9]*University of Florida, Gainesville, Florida 32611*
[10]*Harvard University, Cambridge, Massachusetts 02138*
[11]*University of Illinois, Urbana-Champaign, Illinois 61801*
[12]*Carleton University, Ottawa, Ontario, Canada K1S 5B6 and the Institute of Particle Physics, Canada*
[13]*McGill University, Montréal, Québec, Canada H3A 2T8 and the Institute of Particle Physics, Canada*
[14]*Ithaca College, Ithaca, New York 14850*
[15]*University of Kansas, Lawrence, Kansas 66045*
[16]*University of Minnesota, Minneapolis, Minnesota 55455*
[17]*State University of New York at Albany, Albany, New York 12222*
[18]*Ohio State University, Columbus, Ohio 43210*
[19]*University of Oklahoma, Norman, Oklahoma 73019*
[20]*University of Pittsburgh, Pittsburgh, Pennsylvania 15260*
[21]*Purdue University, West Lafayette, Indiana 47907*
[22]*University of Rochester, Rochester, New York 14627*
[23]*Southern Methodist University, Dallas, Texas 75275*
[24]*Syracuse University, Syracuse, New York 13244*
[25]*University of Texas, Austin, Texas 78712*
[26]*University of Texas–Pan American, Edinburg, Texas 78539*
[27]*Vanderbilt University, Nashville, Tennessee 37235*

(Received 4 January 2001; published 27 December 2001)

We have studied two-body charmless decays of the B meson into the final states $\rho^0\rho^0$, $K^{*0}\rho^0$, $K^{*0}K^{*0}$, $K^{*0}\bar{K}^{*0}$, $K^{*+}\rho^0$, $K^{*+}\bar{K}^{*0}$, and $K^{*+}K^{*-}$ using only decay modes with charged daughter particles. Using 9.7×10^6 $B\bar{B}$ pairs collected with the CLEO detector, we place 90% confidence level upper limits on the branching fractions $(1.4-14.1) \times 10^{-5}$, depending on final state and polarization.

DOI: 10.1103/PhysRevLett.88.021802 PACS numbers: 13.25.Hw, 14.40.Nd

In the standard model, CP violation is introduced by the complex phase in the Cabibbo-Kobayashi-Maskawa quark-mixing matrix. The experimental study of CKM phases will probe the standard model description of CP violation. This may provide a window to new physics. In particular, it has been suggested [1] that we may construct a relationship between charmless $B \to VV$ decays that may lead to the extraction of the angle α. Earlier observations of rare charmless decay modes at CLEO include $B \to K\pi, \pi\pi, \eta K, \rho\pi, \eta' K, \eta K^*$, and $\omega\pi$ [2]. It is natural to extend our search toward other rare charmless B decays.

In this Letter, we present results of searches for B meson decays into the vector mesons ρ^0, K^{*0}, and K^{*+}. The decays are dominated by the $b \to u$ tree-level and $b \to dg$ penguin processes, though other mechanisms may also contribute [3].

The data used in this analysis were collected by the CLEO detector [4] at the Cornell Electron Storage Ring (CESR). The data consist of an integrated luminosity of 9.1 fb^{-1} at the $\Upsilon(4S)$ resonance, corresponding to 9.7×10^6 $B\bar{B}$ events. To determine backgrounds due to nonresonant $e^+e^- \to q\bar{q}$ process, we also collected 4.6 fb^{-1} of continuum data at energies just below the $\Upsilon(4S)$ resonance.

The CLEO detector has 67 tracking layers and a CsI electromagnetic calorimeter that provides efficient π^0 reconstruction, all operating within a 1.5 T superconducting solenoid. The central tracking system, consisting of an inner 6-layer straw tube precision tracker, a 10-layer vertex drift chamber, and a 51-layer main drift chamber, provides a measurement of momenta of charged particles and the vertex position of decaying K_S. It also measures the specific ionization loss, dE/dx, which is used for particle identification. The precision tracker was replaced by a silicon vertex detector for the latter 65% of data taking. Muons are identified using proportional counters placed at various depths in the steel return yoke of the magnet.

B candidates are selected by straightforward criteria based on energy-momentum conservation and event shape. Simulations of the signal and backgrounds are used to refine these criteria and to determine their effectiveness.

The $B \to VV$ decays are reconstructed through the decay channels $B^0 \to \rho^0\rho^0$, $B^0 \to K^{*0}\rho^0$, $B^0 \to K^{*0}K^{*0}$, $B^0 \to K^{*0}\bar{K}^{*0}$, $B^+ \to K^{*+}\rho^0$, $B^+ \to K^{*+}\bar{K}^{*0}$, and $B^0 \to K^{*+}K^{*-}$. We form ρ^0 candidates from $\pi^+\pi^-$ pairs with an invariant mass within 150 MeV$/c^2$ of the nominal ρ^0 mass. $K^{*0}/\bar{K}^{*0}/K^{*\pm}$ candidates are selected from $K^\pm\pi^\mp/K_S^0\pi^\pm$ pairs within 50 MeV$/c^2$ of the nominal K^* mass.

Charged tracks are selected by requiring them to pass quality criteria and must be consistent with production from the primary interaction point (except for pions from K_S^0 decays). The measured specific ionization (dE/dx) of charged kaon and pion candidates is required to be within 3.0σ (standard deviation) of their most probable values. We reject electrons based on dE/dx and the ratio of the track momentum to the associated shower energy in the CsI calorimeter. We reject muons by requiring that the tracks not penetrate the steel absorber past a depth of 3 nuclear interaction lengths. The K_S^0 is selected by requiring a decay vertex displaced from the primary interaction point and an invariant mass within 10 MeV$/c^2$ of the K_S^0 mass.

Fully reconstructed B mesons are selected on the basis of the beam-constrained mass of the candidate, $M_B = \sqrt{E_{\rm beam}^2 - P_{\rm reconstructed}^2}$, and the difference between the reconstructed and beam energies, $\Delta E = E_{\rm reconstructed} - E_{\rm beam}$. ΔE is sensitive to missing or extra particles in the B candidate, as well as incorrect assignment of particle masses. For the fully reconstructed B meson decays in this analysis, the M_B distribution peaks at 5.28 GeV$/c^2$ with a resolution ranging between 2.2–2.6 MeV$/c^2$, and ΔE peaks at zero GeV with a resolution ranging from 16–27 MeV. Candidates are accepted for further analysis if ΔE and M_B are within a signal region $\pm 2\sigma$ around the central signal values for all channels (except $K^{*+}K^{*-}$ where a larger $\pm 2.8\sigma$ region of M_B is used since this involves two K_S^0's and is therefore relatively clean).

The backgrounds consist primarily of continuum events from $e^+e^- \to q\bar{q}$ $(q = u, d, s, c)$ with a 10–15% contribution from B decays, and are estimated from a combination of off-resonance data and $b \to c$ Monte Carlo. Event-shape variables can be used to discriminate against the jetlike continuum events since B mesons are produced nearly at rest. Accordingly, we select only events with $R_2 < 0.5$, where R_2 is the ratio of the second to zeroth Fox-Wolfram moments of the event [5]. In continuum events, momentum conservation aligns the thrust axis of the B candidate with that of the rest of the event while they are almost uncorrelated in $B\bar{B}$ events. This allows additional suppression of continuum by restricting $|\cos\theta_{tt}|$, the angle between the two axes. We require $|\cos\theta_{tt}| < 0.7$ for all decay modes, except for $K^{*+}K^{*-}$, where we use $|\cos\theta_{tt}| < 0.9$.

The four selection criteria discussed above, on M_B, ΔE, R_2, and $\cos\theta_{tt}$, determine the signal efficiency (ε) for each mode. We measure this efficiency using Monte Carlo simulation for each of the 3 possible helicity states of the decay products: 00, $-1-1$ and $+1+1$. Our study indicates that the 00 helicity has slightly lower efficiency than the 11 helicities, since it results in more low momentum charged pion and kaon tracks from the B decay chain, for which the detector has a lower acceptance. In addition, the 00 state will tend to align the vector decay products leading to a higher average R_2, also decreasing the efficiency. We give separate results assuming the signal is 100% 00 helicity or 100% 11 helicity. For any assumed helicity distribution of signal events in the data sample, upper limits can be obtained by linear interpolation.

We find significant double counting of events in the $K^{*0}\rho^0$ channel, caused in most cases by the K/π ambiguity in the $K^{*0} \rightarrow K^+\pi^-$ subdecay. In the final results we count only one entry for each event. We also consider the possibility of crossfeed between different channels of $B \rightarrow VV$ decays. Neglecting the contribution from the forbidden decay mode $B \rightarrow K^{*0}K^{*0}(\Delta S = 2)$, the cross-feed effect is small even if we use the 90% upper limits to evaluate the cross-feed contribution to the yields. We do not correct for this contribution when extracting the upper limits.

There are several sources of systematic error. A substantial contribution comes from the uncertainty in track efficiency, which is 1.5% per charged track. For B decay modes with $K^{*\pm}$, there is an additional 5% uncertainty due to the K_S^0 vertex requirement. In addition, we estimate 1% per charged track uncertainty due to the dE/dx requirement. Additional systematic errors include 7% uncertainty from the thrust criterion and 3% from the ΔE and M_B requirements. Uncertainties due to Monte Carlo statistics range from 2% to 6%, depending on B decay mode.

The results of this analysis are summarized in Table I and displayed in Fig. 1; we see no statistically compelling signal in any individual decay channel. To calculate 90% confidence level (C.L.) upper limits on the number of signal events ($n_{\mathrm{u.l.}}$) in each channel, we used a method based on the unified frequentist approach proposed by Feldman and Cousins [6] and adopted by the Particle Data Group [7]. We construct the confidence belts with 90% coverage using the likelihood ratio as the ordering principle for Poisson process when the total number of observed events n consists of signal events with mean n_S and background events with mean n_B:

$$P(n \mid n_S, n_B) = e^{-(n_S + n_B)} \frac{(n_S + n_B)^n}{n!} .$$

We assume that the background mean is not well known but fluctuates around the measured background $b = n_{b\rightarrow c} + n_{\mathrm{off}}$ with Poisson probability and we summed over it:

$$P(n \mid n_S) = \sum_{n_B} P(n \mid n_S, n_B) e^{-b} \frac{b^{n_B}}{n_B!} .$$

To include the systematic error on the reconstruction efficiency we assume a normal probability distribution and convolute it with the $P(n \mid n_S)$ probability [8]. We also calculate the sensitivity of the experiment as the average signal upper limit that would be obtained by an ensemble of experiments with no true signal [6]. The upper limits on the branching ratios are then calculated from the formula

$$\mathcal{B}(B \rightarrow VV) = \frac{n_{\mathrm{u.l.}}}{n_{B\bar{B}} \times \varepsilon \times \prod_{\mathrm{B}}} ,$$

TABLE I. The 90% C.L. upper limits for the $B \rightarrow VV$ decay modes ($\mathcal{B}_{\mathrm{CLEO}}$) are shown in units of 10^{-6}, along with the corresponding theoretical predictions ($\mathcal{B}_{\mathrm{theory}}$) [3]. n_{obs} is the number of observed events, n_{off} is the off-resonance background (normalized), $n_{b\rightarrow c}$ is the $B\bar{B}$ background estimate (from Monte Carlo), $n_{\mathrm{u.l.}}$ is the corresponding upper limit including systematic error and background statistics, and n_{sen} is the sensitivity of the measurement according to Feldman and Cousins' definition [6]. The reconstruction efficiency (ε) is also shown along with the systematic error ($\delta\varepsilon$).

Mode	Helicity	n_{obs}	n_{off}	$n_{b\rightarrow c}$	ε (%)	$\delta\varepsilon/\varepsilon$ (%)	$n_{\mathrm{u.l.}}$	n_{sen}	$\mathcal{B}_{\mathrm{CLEO}}$[a] ($\times 10^{-6}$)	$\mathcal{B}_{\mathrm{theory}}$ ($\times 10^{-6}$)
$\rho^0\rho^0$	00	54	67	7.6	13	11	5.9	23	<18	0.54–2.5
	11				17	11			<14	
$K^{*0}\rho^0$	00	96	92	14	12	11	16	27	<34	0.7–6.2
	11				18	11			<24	
$K^{*0}K^{*0}$	00	22	14	1.6	11	11	18	11	<37	
	11				14	11			<29	
$K^{*0}\bar{K}^{*0}$	00	12	16	1.4	12	11	5.5	12	<22	0.28–0.96
	11				14	11			<19	
$K^{*+}\rho^0$	00	12	5.9	2.4	7.8	13	13	8.3	<74	0.8–14
	11				12	13			<49	
$K^{*+}\bar{K}^{*0}$	00	3	0.0	0.0	7.3	13	7.5	2.5	<71	0.29–1.8
	11				10	13			<48	
$K^{*+}K^{*-}$	00	0	2.0	0.0	6.6	17	1.5	4.6	<141	
	11				10	16			<89	

[a]$\mathcal{B}_{\mathrm{CLEO}}$ is calculated based on the sensitivity of the measurement (n_{sen}) instead of the signal upper limit ($n_{\mathrm{u.l.}}$) if $n_{\mathrm{sen}} > n_{\mathrm{u.l.}}$.

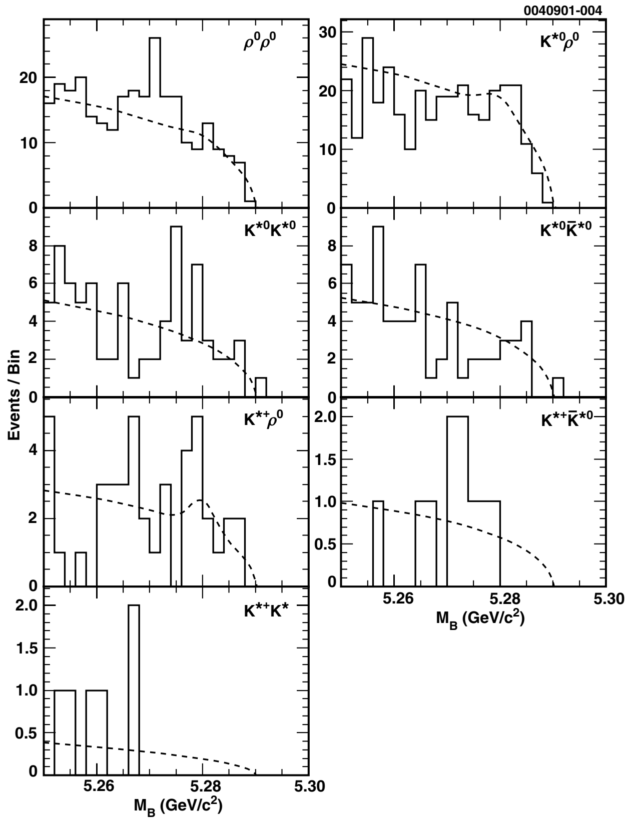

FIG. 1. B meson mass distributions for the seven modes discussed in the text. The histograms represent the data and the dashed lines represent the Monte Carlo prediction for the continuum plus $B\bar{B}$ background.

where $n_{B\bar{B}}$ is the number of $B\bar{B}$ meson pairs in the data sample, and $\prod_{\mathcal{B}}$ is the product over all the relevant branching fractions of the vector meson decay chain. We assume equal branching fractions for $\Upsilon(4S) \to B^0\bar{B}^0$ and B^+B^-.

To summarize, we set 90% C.L. upper limits on branching fractions of seven $B \to VV$ charmless decay modes. Theoretical predictions for the branching fractions of these modes tend to be near 10^{-6}. Thus our results are consistent with theoretical calculations based on the standard model. In order to challenge these predictions data samples of the order of 10^8 $B\bar{B}$ mesons would be required.

[1] D. Atwood and A. Soni, Phys. Rev. D **59**, 13 007 (1999).

[2] CLEO Collaboration, D. Cronin-Hennessy *et al.,* Phys. Rev. Lett. **85**, 525 (2000); CLEO Collaboration, S. J. Richichi *et al.,* Phys. Rev. Lett. **85**, 520 (2000); CLEO Collaboration, R. Godang *et al.,* Phys. Rev. Lett. **80**, 3456 (1998); CLEO Collaboration, B. Behrens *et al.,* Phys. Rev. Lett. **80**, 3710 (1998); CLEO Collaboration, T. Bergfeld *et al.,* Phys. Rev. Lett. **81**, 272 (1998); CLEO Collaboration, D. M. Asner *et al.,* Phys. Rev. D **53**, 1039 (1996).

[3] A. Ali, G. Kramer, and C.-D. Lü, Phys. Rev. D **58**, 94009 (1998); A. Deandrea *et al.,* Phys. Lett. B **320**, 170 (1994); N. G. Deshpande, in *B Decays,* edited by S. Stone (World Scientific, Singapore, 1994); D. Du and Z. Xing, Phys. Rev. D **48**, 4155 (1993); L. Chau *et al.,* Phys. Rev. D **45**, 3143 (1992); G. Kramer and W. F. Palmer, Phys. Rev. D **46**, 2969 (1992); M. Bauer, B. Stech, and M. Wirbel, Z. Phys. C **34**, 103 (1987).

[4] CLEO Collaboration, Y. Kubota *et al.,* Nucl. Instrum. Methods Phys. Res., Sect. A **320**, 66 (1992).

[5] G. Fox and S. Wolfram, Phys. Rev. Lett. **41**, 1581 (1978).

[6] G. J. Feldman and R. D. Cousins, Phys. Rev. D **57**, 3873 (1998).

[7] Particle Data Group, D. E. Groom *et al.,* Eur. Phys. J. C **15**, 1 (2000).

[8] R. D. Cousins and V. L. Highland, Nucl. Instrum. Methods Phys. Res., Sect. A **320**, 331 (1992).