Rare B Decays into States Containing a J/ψ Meson and a Meson with $s\bar{s}$ Quark Content

B. Aubert,[1] D. Boutigny,[1] J.-M. Gaillard,[1] A. Hicheur,[1] Y. Karyotakis,[1] J. P. Lees,[1] P. Robbe,[1] V. Tisserand,[1] A. Zghiche,[1]
A. Palano,[2] A. Pompili,[2] J. C. Chen,[3] N. D. Qi,[3] G. Rong,[3] P. Wang,[3] Y. S. Zhu,[3] G. Eigen,[4] I. Ofte,[4] B. Stugu,[4]
G. S. Abrams,[5] A. W. Borgland,[5] A. B. Breon,[5] D. N. Brown,[5] J. Button-Shafer,[5] R. N. Cahn,[5] E. Charles,[5] M. S. Gill,[5]
A. V. Gritsan,[5] Y. Groysman,[5] R. G. Jacobsen,[5] R. W. Kadel,[5] J. Kadyk,[5] L. T. Kerth,[5] Yu. G. Kolomensky,[5] J. F. Kral,[5]
C. LeClerc,[5] M. E. Levi,[5] G. Lynch,[5] L. M. Mir,[5] P. J. Oddone,[5] T. J. Orimoto,[5] M. Pripstein,[5] N. A. Roe,[5] A. Romosan,[5]
M. T. Ronan,[5] V. G. Shelkov,[5] A. V. Telnov,[5] W. A. Wenzel,[5] T. J. Harrison,[6] C. M. Hawkes,[6] D. J. Knowles,[6]
S. W. O'Neale,[6] R. C. Penny,[6] A. T. Watson,[6] N. K. Watson,[6] T. Deppermann,[7] K. Goetzen,[7] H. Koch,[7] B. Lewandowski,[7]
K. Peters,[7] H. Schmuecker,[7] M. Steinke,[7] N. R. Barlow,[8] W. Bhimji,[8] J. T. Boyd,[8] N. Chevalier,[8] P. J. Clark,[8]
W. N. Cottingham,[8] C. Mackay,[8] F. F. Wilson,[8] K. Abe,[9] C. Hearty,[9] T. S. Mattison,[9] J. A. McKenna,[9] D. Thiessen,[9]
S. Jolly,[10] A. K. McKemey,[10] V. E. Blinov,[11] A. D. Bukin,[11] A. R. Buzykaev,[11] V. B. Golubev,[11] V. N. Ivanchenko,[11]
A. A. Korol,[11] E. A. Kravchenko,[11] A. P. Onuchin,[11] S. I. Serednyakov,[11] Yu. I. Skovpen,[11] A. N. Yushkov,[11] D. Best,[12]
M. Chao,[12] D. Kirkby,[12] A. J. Lankford,[12] M. Mandelkern,[12] S. McMahon,[12] D. P. Stoker,[12] K. Arisaka,[13]
C. Buchanan,[13] S. Chun,[13] D. B. MacFarlane,[14] S. Prell,[14] Sh. Rahatlou,[14] G. Raven,[14] V. Sharma,[14] J. W. Berryhill,[15]
C. Campagnari,[15] B. Dahmes,[15] P. A. Hart,[15] N. Kuznetsova,[15] S. L. Levy,[15] O. Long,[15] A. Lu,[15] M. A. Mazur,[15]
J. D. Richman,[15] W. Verkerke,[15] J. Beringer,[16] A. M. Eisner,[16] M. Grothe,[16] C. A. Heusch,[16] W. S. Lockman,[16]
T. Pulliam,[16] T. Schalk,[16] R. E. Schmitz,[16] B. A. Schumm,[16] A. Seiden,[16] M. Turri,[16] W. Walkowiak,[16] D. C. Williams,[16]
M. G. Wilson,[16] E. Chen,[17] G. P. Dubois-Felsmann,[17] A. Dvoretskii,[17] D. G. Hitlin,[17] F. C. Porter,[17] A. Ryd,[17] A. Samuel,[17]
S. Yang,[17] S. Jayatilleke,[18] G. Mancinelli,[18] B. T. Meadows,[18] M. D. Sokoloff,[18] T. Barillari,[19] P. Bloom,[19] W. T. Ford,[19]
U. Nauenberg,[19] A. Olivas,[19] P. Rankin,[19] J. Roy,[19] J. G. Smith,[19] W. C. van Hoek,[19] L. Zhang,[19] J. Blouw,[20]
J. L. Harton,[20] M. Krishnamurthy,[20] A. Soffer,[20] W. H. Toki,[20] R. J. Wilson,[20] J. Zhang,[20] D. Altenburg,[21] T. Brandt,[21]
J. Brose,[21] T. Colberg,[21] M. Dickopp,[21] R. S. Dubitzky,[21] A. Hauke,[21] E. Maly,[21] R. Müller-Pfefferkorn,[21] S. Otto,[21]
K. R. Schubert,[21] R. Schwierz,[21] B. Spaan,[21] L. Wilden,[21] D. Bernard,[22] G. R. Bonneaud,[22] F. Brochard,[22]
J. Cohen-Tanugi,[22] S. Ferrag,[22] S. T'Jampens,[22] Ch. Thiebaux,[22] G. Vasileiadis,[22] M. Verderi,[22] A. Anjomshoaa,[23]
R. Bernet,[23] A. Khan,[23] D. Lavin,[23] F. Muheim,[23] S. Playfer,[23] J. E. Swain,[23] J. Tinslay,[23] M. Falbo,[24] C. Borean,[25]
C. Bozzi,[25] L. Piemontese,[25] A. Sarti,[25] E. Treadwell,[26] F. Anulli,[27,*] R. Baldini-Ferroli,[27] A. Calcaterra,[27]
R. de Sangro,[27] D. Falciai,[27] G. Finocchiaro,[27] P. Patteri,[27] I. M. Peruzzi,[27,*] M. Piccolo,[27] A. Zallo,[27] S. Bagnasco,[28]
A. Buzzo,[28] R. Contri,[28] G. Crosetti,[28] M. Lo Vetere,[28] M. Macri,[28] M. R. Monge,[28] S. Passaggio,[28] F. C. Pastore,[28]
C. Patrignani,[28] E. Robutti,[28] A. Santroni,[28] S. Tosi,[28] M. Morii,[29] R. Bartoldus,[30] G. J. Grenier,[30] U. Mallik,[30]
J. Cochran,[31] H. B. Crawley,[31] J. Lamsa,[31] W. T. Meyer,[31] E. I. Rosenberg,[31] J. Yi,[31] M. Davier,[32] G. Grosdidier,[32]
A. Höcker,[32] H. M. Lacker,[32] S. Laplace,[32] F. Le Diberder,[32] V. Lepeltier,[32] A. M. Lutz,[32] T. C. Petersen,[32]
S. Plaszczynski,[32] M. H. Schune,[32] L. Tantot,[32] S. Trincaz-Duvoid,[32] G. Wormser,[32] R. M. Bionta,[33] V. Brigljević,[33]
D. J. Lange,[33] M. Mugge,[33] K. van Bibber,[33] D. M. Wright,[33] A. J. Bevan,[34] J. R. Fry,[34] E. Gabathuler,[34] R. Gamet,[34]
M. George,[34] M. Kay,[34] D. J. Payne,[34] R. J. Sloane,[34] C. Touramanis,[34] M. L. Aspinwall,[35] D. A. Bowerman,[35]
P. D. Dauncey,[35] U. Egede,[35] I. Eschrich,[35] G. W. Morton,[35] J. A. Nash,[35] P. Sanders,[35] D. Smith,[35] G. P. Taylor,[35]
J. J. Back,[36] G. Bellodi,[36] P. Dixon,[36] P. F. Harrison,[36] R. J. L. Potter,[36] H. W. Shorthouse,[36] P. Strother,[36] P. B. Vidal,[36]
G. Cowan,[37] H. U. Flaecher,[37] S. George,[37] M. G. Green,[37] A. Kurup,[37] C. E. Marker,[37] T. R. McMahon,[37] S. Ricciardi,[37]
F. Salvatore,[37] G. Vaitsas,[37] M. A. Winter,[37] D. Brown,[38] C. L. Davis,[38] J. Allison,[39] R. J. Barlow,[39] A. C. Forti,[39]
F. Jackson,[39] G. D. Lafferty,[39] N. Savvas,[39] J. H. Weatherall,[39] J. C. Williams,[39] A. Farbin,[40] A. Jawahery,[40] V. Lillard,[40]
D. A. Roberts,[40] J. R. Schieck,[40] G. Blaylock,[41] C. Dallapiccola,[41] K. T. Flood,[41] S. S. Hertzbach,[41] R. Kofler,[41]
V. B. Koptchev,[41] T. B. Moore,[41] H. Staengle,[41] S. Willocq,[41] B. Brau,[42] R. Cowan,[42] G. Sciolla,[42] F. Taylor,[42]
R. K. Yamamoto,[42] M. Milek,[43] P. M. Patel,[43] F. Palombo,[44] J. M. Bauer,[45] L. Cremaldi,[45] V. Eschenburg,[45] R. Kroeger,[45]
J. Reidy,[45] D. A. Sanders,[45] D. J. Summers,[45] C. Hast,[46] P. Taras,[46] H. Nicholson,[47] C. Cartaro,[48] N. Cavallo,[48]
G. De Nardo,[48] F. Fabozzi,[48] C. Gatto,[48] L. Lista,[48] P. Paolucci,[48] D. Piccolo,[48] C. Sciacca,[48] J. M. LoSecco,[49]
J. R. G. Alsmiller,[50] T. A. Gabriel,[50] J. Brau,[51] R. Frey,[51] M. Iwasaki,[51] C. T. Potter,[51] N. B. Sinev,[51] D. Strom,[51]
E. Torrence,[51] F. Colecchia,[52] A. Dorigo,[52] F. Galeazzi,[52] M. Margoni,[52] M. Morandin,[52] M. Posocco,[52] M. Rotondo,[52]
F. Simonetto,[52] R. Stroili,[52] C. Voci,[52] M. Benayoun,[53] H. Briand,[53] J. Chauveau,[53] P. David,[53] Ch. de la Vaissière,[53]
L. Del Buono,[53] O. Hamon,[53] Ph. Leruste,[53] J. Ocariz,[53] M. Pivk,[53] L. Roos,[53] J. Stark,[53] P. F. Manfredi,[54] V. Re,[54]
V. Speziali,[54] L. Gladney,[55] Q. H. Guo,[55] J. Panetta,[55] C. Angelini,[56] G. Batignani,[56] S. Bettarini,[56] M. Bondioli,[56]
F. Bucci,[56] G. Calderini,[56] E. Campagna,[56] M. Carpinelli,[56] F. Forti,[56] M. A. Giorgi,[56] A. Lusiani,[56] G. Marchiori,[56]

0031-9007/03/91(7)/071801(7)$20.00

F. Martinez-Vidal,[56] M. Morganti,[56] N. Neri,[56] E. Paoloni,[56] M. Rama,[56] G. Rizzo,[56] F. Sandrelli,[56] G. Triggiani,[56]
J. Walsh,[56] M. Haire,[57] D. Judd,[57] K. Paick,[57] L. Turnbull,[57] D. E. Wagoner,[57] J. Albert,[58] P. Elmer,[58] C. Lu,[58]
V. Miftakov,[58] J. Olsen,[58] S. F. Schaffner,[58] A. J. S. Smith,[58] A. Tumanov,[58] E.W. Varnes,[58] F. Bellini,[59] G. Cavoto,[58,59]
D. del Re,[59] R. Faccini,[14,59] F. Ferrarotto,[59] F. Ferroni,[59] E. Leonardi,[59] M. A. Mazzoni,[59] S. Morganti,[59] G. Piredda,[59]
F. Safai Tehrani,[59] M. Serra,[59] C. Voena,[59] S. Christ,[60] G. Wagner,[60] R. Waldi,[60] T. Adye,[61] N. De Groot,[61] B. Franek,[61]
N. I. Geddes,[61] G. P. Gopal,[61] S. M. Xella,[61] R. Aleksan,[62] S. Emery,[62] A. Gaidot,[62] P.-F. Giraud,[62]
G. Hamel de Monchenault,[62] W. Kozanecki,[62] M. Langer,[62] G.W. London,[62] B. Mayer,[62] G. Schott,[62] B. Serfass,[62]
G. Vasseur,[62] Ch. Yeche,[62] M. Zito,[62] M.V. Purohit,[63] A.W. Weidemann,[63] F. X. Yumiceva,[63] I. Adam,[64] D. Aston,[64]
N. Berger,[64] A. M. Boyarski,[64] M. R. Convery,[64] D. P. Coupal,[64] D. Dong,[64] J. Dorfan,[64] W. Dunwoodie,[64] R. C. Field,[64]
T. Glanzman,[64] S. J. Gowdy,[64] E. Grauges,[64] T. Haas,[64] T. Hadig,[64] V. Halyo,[64] T. Himel,[64] T. Hryn'ova,[64] M. E. Huffer,[64]
W. R. Innes,[64] C. P. Jessop,[64] M. H. Kelsey,[64] P. Kim,[64] M. L. Kocian,[64] U. Langenegger,[64] D.W. G. S. Leith,[64] S. Luitz,[64]
V. Luth,[64] H. L. Lynch,[64] H. Marsiske,[64] S. Menke,[64] R. Messner,[64] D. R. Muller,[64] C. P. O'Grady,[64] V. E. Ozcan,[64]
A. Perazzo,[64] M. Perl,[64] S. Petrak,[64] B. N. Ratcliff,[64] S. H. Robertson,[64] A. Roodman,[64] A. A. Salnikov,[64]
T. Schietinger,[64] R. H. Schindler,[64] J. Schwiening,[64] G. Simi,[64] A. Snyder,[64] A. Soha,[64] S. M. Spanier,[64] J. Stelzer,[64]
D. Su,[64] M. K. Sullivan,[64] H. A. Tanaka,[64] J. Va'vra,[64] S. R. Wagner,[64] M. Weaver,[64] A. J. R. Weinstein,[64]
W. J. Wisniewski,[64] D. H. Wright,[64] C. C. Young,[64] P. R. Burchat,[65] C. H. Cheng,[65] T. I. Meyer,[65] C. Roat,[65]
R. Henderson,[66] W. Bugg,[67] H. Cohn,[67] J. M. Izen,[68] I. Kitayama,[68] X. C. Lou,[68] F. Bianchi,[69] M. Bona,[69] D. Gamba,[69]
L. Bosisio,[70] G. Della Ricca,[70] S. Dittongo,[70] L. Lanceri,[70] P. Poropat,[70] L. Vitale,[70] G. Vuagnin,[70] R. S. Panvini,[71]
S.W. Banerjee,[72] C. M. Brown,[72] D. Fortin,[72] P. D. Jackson,[72] R. Kowalewski,[72] J. M. Roney,[72] H. R. Band,[73] S. Dasu,[73]
M. Datta,[73] A. M. Eichenbaum,[73] H. Hu,[73] J. R. Johnson,[73] R. Liu,[73] F. Di Lodovico,[73] A. Mohapatra,[73] Y. Pan,[73]
R. Prepost,[73] I. J. Scott,[73] S. J. Sekula,[73] J. H. von Wimmersperg-Toeller,[73] J. Wu,[73] S. L. Wu,[73] Z. Yu,[73] and H. Neal[74]

(The *BABAR* Collaboration)

[1]*Laboratoire de Physique des Particules, F-74941 Annecy-le-Vieux, France*
[2]*Università di Bari, Dipartimento di Fisica and INFN, I-70126 Bari, Italy*
[3]*Institute of High Energy Physics, Beijing 100039, China*
[4]*University of Bergen, Institute of Physics, N-5007 Bergen, Norway*
[5]*Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA*
[6]*University of Birmingham, Birmingham, B15 2TT, United Kingdom*
[7]*Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany*
[8]*University of Bristol, Bristol BS8 1TL, United Kingdom*
[9]*University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1*
[10]*Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom*
[11]*Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia*
[12]*University of California at Irvine, Irvine, California 92697, USA*
[13]*University of California at Los Angeles, Los Angeles, California 90024, USA*
[14]*University of California at San Diego, La Jolla, California 92093, USA*
[15]*University of California at Santa Barbara, Santa Barbara, California 93106, USA*
[16]*University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA*
[17]*California Institute of Technology, Pasadena, California 91125, USA*
[18]*University of Cincinnati, Cincinnati, Ohio 4522, USA1*
[19]*University of Colorado, Boulder, Colorado 80309, USA*
[20]*Colorado State University, Fort Collins, Colorado 80523, USA*
[21]*Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany*
[22]*Ecole Polytechnique, LLR, F-91128 Palaiseau, France*
[23]*University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom*
[24]*Elon University, Elon University, North Carolina 27244-2010, USA*
[25]*Università di Ferrara, Dipartimento di Fisica and INFN, I-44100 Ferrara, Italy*
[26]*Florida A&M University, Tallahassee, Florida 32307, USA*
[27]*Laboratori Nazionali di Frascati dell'INFN, I-00044 Frascati, Italy*
[28]*Università di Genova, Dipartimento di Fisica and INFN, I-16146 Genova, Italy*
[29]*Harvard University, Cambridge, Massachusetts 02138, USA*
[30]*University of Iowa, Iowa City, Iowa 52242, USA*
[31]*Iowa State University, Ames, Iowa 50011-3160, USA*
[32]*Laboratoire de l'Accélérateur Linéaire, F-91898 Orsay, France*

[33]Lawrence Livermore National Laboratory, Livermore, California 94550, USA
[34]University of Liverpool, Liverpool L69 3BX, United Kingdom
[35]University of London, Imperial College, London SW7 2BW, United Kingdom
[36]Queen Mary, University of London, E1 4NS, United Kingdom
[37]University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom
[38]University of Louisville, Louisville, Kentucky 40292, USA
[39]University of Manchester, Manchester M13 9PL, United Kingdom
[40]University of Maryland, College Park, Maryland 20742, USA
[41]University of Massachusetts, Amherst, Massachusetts 01003, USA
[42]Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA
[43]McGill University, Montréal, Quebec, Canada H3A 2T8
[44]Università di Milano, Dipartimento di Fisica and INFN, I-20133 Milano, Italy
[45]University of Mississippi, University, Mississippi 38677, USA
[46]Université de Montréal, Laboratoire René J. A. Lévesque, Montréal, Quebec, Canada H3C 3J7
[47]Mount Holyoke College, South Hadley, Massachusetts 01075, USA
[48]Università di Napoli Federico II, Dipartimento di Scienze Fisiche and INFN, I-80126, Napoli, Italy
[49]University of Notre Dame, Notre Dame, Indiana 46556, USA
[50]Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA
[51]University of Oregon, Eugene, Oregon 97403, USA
[52]Università di Padova, Dipartimento di Fisica and INFN, I-35131 Padova, Italy
[53]Universités Paris VI et VII, Lab de Physique Nucléaire H. E., F-75252 Paris, France
[54]Università di Pavia, Dipartimento di Elettronica and INFN, I-27100 Pavia, Italy
[55]University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
[56]Università di Pisa, Scuola Normale Superiore and INFN, I-56010 Pisa, Italy
[57]Prairie View A&M University, Prairie View, Texas 77446, USA
[58]Princeton University, Princeton, New Jersey 08544, USA
[59]Università di Roma La Sapienza, Dipartimento di Fisica and INFN, I-00185 Roma, Italy
[60]Universität Rostock, D-18051 Rostock, Germany
[61]Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, United Kingdom
[62]DAPNIA, Commissariat à l'Energie Atomique/Saclay, F-91191 Gif-sur-Yvette, France
[63]University of South Carolina, Columbia, South Carolina 29208, USA
[64]Stanford Linear Accelerator Center, Stanford, California 94309, USA
[65]Stanford University, Stanford, California 94305-4060, USA
[66]TRIUMF, Vancouver, British Columbia, Canada V6T 2A3
[67]University of Tennessee, Knoxville, Tennessee 37996, USA
[68]University of Texas at Dallas, Richardson, Texas 75083, USA
[69]Università di Torino, Dipartimento di Fisica Sperimentale and INFN, I-10125 Torino, Italy
[70]Università di Trieste, Dipartimento di Fisica and INFN, I-34127 Trieste, Italy
[71]Vanderbilt University, Nashville, Tennessee 37235, USA
[72]University of Victoria, Victoria, British Columbia, Canada V8W 3P6
[73]University of Wisconsin, Madison, Wisconsin 53706, USA
[74]Yale University, New Haven, Connecticut 06511, USA

(Received 3 April 2003; published 13 August 2003)

We report a study of the B meson decays, $B^+ \rightarrow J/\psi\phi K^+$, $B^0 \rightarrow J/\psi\phi K^0_S$, $B^0 \rightarrow J/\psi\phi$, $B^0 \rightarrow J/\psi\eta$, and $B^0 \rightarrow J/\psi\eta'$ using 56×10^6 $B\overline{B}$ events collected at the $\Upsilon(4S)$ resonance with the *BABAR* detector at the PEP-II e^+e^- asymmetric-energy storage ring. We measure the branching fractions $\mathcal{B}(B^+ \rightarrow J/\psi\phi K^+) = (4.4 \pm 1.4(\text{stat}) \pm 0.5(\text{syst})) \times 10^{-5}$ and $\mathcal{B}(B^0 \rightarrow J/\psi\phi K^0_S) = (5.1 \pm 1.9(\text{stat}) \pm 0.5(\text{syst})) \times 10^{-5}$, and set upper limits at 90% confidence level for the branching fractions $\mathcal{B}(B^0 \rightarrow J/\psi\phi) < 9.2 \times 10^{-6}$, $\mathcal{B}(B^0 \rightarrow J/\psi\eta) < 2.7 \times 10^{-5}$, and $\mathcal{B}(B^0 \rightarrow J/\psi\eta') < 6.3 \times 10^{-5}$.

DOI: 10.1103/PhysRevLett.91.071801 PACS numbers: 13.25.Hw, 11.30.Er, 12.15.Hh

The observation [1] of CP violating B meson decays into CP eigenstates with charmonium provides major evidence for the Cabibbo-Kobayashi-Maskawa model [2] and an important advance in our understanding of the standard model. This motivates the search for additional CP eigenstate decay modes of neutral B mesons to enable new CP tests of the standard model.

Recent observations of the B meson decays $B \rightarrow J/\psi\pi$ [3] and $J/\psi\rho$ [4] indicate the Cabibbo-suppressed transitions $b \rightarrow c\bar{c}d$ via the color-suppressed diagram shown in Fig. 1(a). Here we present a search for similar color-suppressed modes except with hidden strangeness, $s\bar{s}$, in the final state: $B \rightarrow J/\psi\eta$, $J/\psi\eta'$, $J/\psi\phi$, and $J/\psi\phi K$. The decays $B^0 \rightarrow J/\psi\eta$ and $B^0 \rightarrow J/\psi\eta'$ occur via the

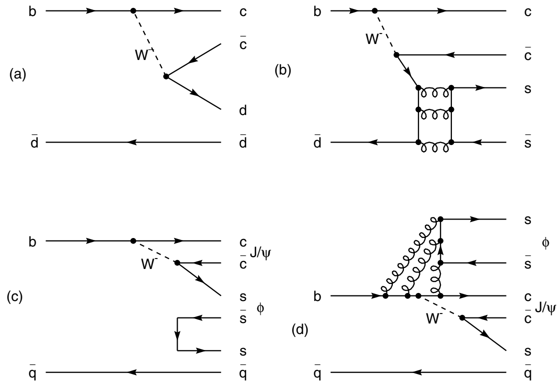

FIG. 1. Quark diagrams: (a) Tree diagram for $B \to J/\psi\pi$ and $J/\psi\rho$, (b) rescattering for $B \to J/\psi\phi$, (c) strange sea quarks, and (d) gluon coupling for $B \to J/\psi\phi K$.

same diagram, Fig. 1(a), and should have a comparable rate. If large enough samples can be isolated, these *CP* eigenstates could be used to test *CP* violation [5]. Models based on the heavy quark factorization approximation by Deandrea *et al.* [6] are used to predict that the branching fraction for $B^0 \to J/\psi\eta$ is a factor of 4 smaller than that for $B^0 \to J/\psi\pi^0$. The decay $B^0 \to J/\psi\phi$ is likely a color-suppressed mode with rescattering as shown in Fig. 1(b), so its absence would indicate that the rescattering effects are negligible. The decay $B \to J/\psi\phi K$ is a Cabibbo-allowed and color-suppressed decay via the transition $b\overline{q} \to c\overline{c}s\overline{s}s\overline{q}$, where the $s\overline{s}$ quark pairs are produced from sea quarks or are connected via gluons as shown in Figs. 1(c) and 1(d), respectively. This particular three-body decay may be of interest in the search for hybrid charmonium states that decay to the final state $J/\psi\phi$ [7]. In this Letter, we report on branching fractions or upper limits for $J/\psi\eta$, $J/\psi\eta'$, $J/\psi\phi$, $J/\psi\phi K^+$, and $J/\psi\phi K^0_S$.

The data used in this analysis were collected at the PEP-II asymmetric-energy e^+e^- storage ring with the *BABAR* detector, fully described elsewhere [8] with a brief overview in [3]. The *BABAR* detector contains a silicon vertex tracker and a drift chamber in a 1.5-T solenoidal magnetic field to detect charged particles and measure their momentum and energy loss. Photons and neutral hadrons are detected in a CsI(Tl) calorimeter. An internally reflecting ring-imaging Cherenkov detector is used for charged particle identification (PID). Penetrating muons and neutral hadrons are identified by the steel flux return.

The data correspond to a total integrated luminosity of $50.9\ \text{fb}^{-1}$ taken on the $\Upsilon(4S)$ resonance and $6.3\ \text{fb}^{-1}$ taken off resonance at an energy 0.04 GeV below the $\Upsilon(4S)$ mass and below the threshold for $B\overline{B}$ production. In this sample, there are $(55.5 \pm 0.6) \times 10^6$ $B\overline{B}$ events ($N_{B\overline{B}}$).

In this analysis, the charged track selection requirements and the selection of photon, electron, and muon candidates use the methods from previous publications [9], and the selection of kaon and pion candidates follows [10].

TABLE I. Mass regions for selection of intermediate particles.

Mode	Mass range (GeV/c^2)				
$J/\psi \to e^+e^-$	2.95	$<$	$M(e^+e^-)$	$<$	3.14
$J/\psi \to \mu^+\mu^-$	3.06	$<$	$M(\mu^+\mu^-)$	$<$	3.14
$\phi \to K^+K^-$	1.004	$<$	$M(K^+K^-)$	$<$	1.034
$K^0_S \to \pi^+\pi^-$	0.489	$<$	$M(\pi^+\pi^-)$	$<$	0.507
$\eta \to \gamma\gamma$	0.529	$<$	$M(\gamma\gamma)$	$<$	0.565
$\eta \to \pi^+\pi^-\pi^0$	0.529	$<$	$M(\pi^+\pi^-\pi^0)$	$<$	0.565
$\eta' \to \eta\pi^+\pi^-$	0.938	$<$	$M(\eta\pi^+\pi^-)$	$<$	0.978
$\pi^0 \to \gamma\gamma$	0.120	$<$	$M(\gamma\gamma)$	$<$	0.150

The intermediate states in this analysis, $J/\psi(ee, \mu\mu)$, $\phi(K^+K^-)$, $\eta(\gamma\gamma, \pi^+\pi^-\pi^0)$, $\eta'[\eta(\gamma\gamma)\pi^+\pi^-]$, $\pi^0(\gamma\gamma)$, and $K^0_S(\pi^+\pi^-)$, are selected with the mass intervals in Table I. Since $B^0 \to J/\psi\eta$ and $B^0 \to J/\psi\eta'$ involve decays of a pseudoscalar meson into a vector and a pseudoscalar meson, the angular distribution is proportional to $\sin^2\theta_\ell$, where θ_ℓ is the helicity angle [3] of the lepton from the J/ψ. Hence, an additional requirement of $|\cos\theta_\ell| < 0.8$ is applied to reject continuum and other backgrounds. The η candidates are rejected if either of the associated photons, in combination with any other photon in the event, forms a $\gamma\gamma$ mass within 20 MeV/c^2 of the π^0 mass. For the mode $B^0 \to J/\psi\eta(\gamma\gamma)$, the η candidate is required to have $|\cos\theta^\eta_\gamma| < 0.8$, where θ^η_γ is the photon helicity angle in the η rest frame. This rejects combinatoric background due to random pairs of photons that typically have a photon helicity angle that peaks at 0° or 180°. For the $\eta' \to \eta(\gamma\gamma)\pi^+\pi^-$ candidates, we use the same η selection criteria for the η described above, including the π^0 veto.

An additional requirement separates two-jet continuum events from the more spherical B meson decays. The angle θ_T between the thrust [3] direction of the B meson candidate and the thrust direction of the remaining tracks in the event is calculated. We require $|\cos\theta_T| < 0.8$, since these thrust axes are uncorrelated and the distribution in $\cos\theta_T$ is flat for $B\overline{B}$ events, while the distribution is peaked at $\cos\theta_T = \pm 1$ for continuum events.

The intermediate candidates are combined to construct the B candidates for the six decay modes under study. The estimation of the signal and the background employs two kinematic variables: the energy difference ΔE between the energy of the B candidate and the beam energy E^*_b in the $\Upsilon(4S)$ rest frame; and the energy-substituted mass $m_{\text{ES}} = \sqrt{(E^*_b)^2 - (P^*_B)^2}$, where P^*_B is the reconstructed momentum of the B candidate in the $\Upsilon(4S)$ frame. Typically, these two weakly correlated variables form a two-dimensional Gaussian distribution for the B meson signal but not for background. The resolutions in ΔE and

TABLE II. Branching fractions and 90% C.L. upper limits.

	Signal region								
Mode	ΔE (MeV)	$\lvert m_{\mathrm{ES}} - m_B \rvert$ (MeV$/c^2$)	Efficiency	n_0	$n_b \pm \sigma_b$	$N_{90\%}$	P value	90% C.L.U.L. (10^{-5})	Branching fraction (10^{-5})
$J/\psi\phi K^+$	57.0	8.0	10.6%	23	7.8 ± 0.6		$(0.77\text{–}2.4) \times 10^{-5}$		$4.4 \pm 1.4 \pm 0.5$
$J/\psi\phi K^0_S$	57.0	8.0	8.6%	13	3.3 ± 0.4		$(4.2\text{–}13) \times 10^{-5}$		$5.1 \pm 1.9 \pm 0.5$
$J/\psi\phi K^0$									$10.2 \pm 3.8 \pm 1.0$
$J/\psi\phi$	57.0	8.0	12.1%	1	0.3 ± 0.2	3.60		<0.9	$0.18 \pm 0.26 \pm 0.03$
$J/\psi\eta'$	100.0	10.0	2.5%	0	0.5 ± 0.3	1.81		<6.3	$-1.7 \pm 1.0 \pm 0.2$
$J/\psi\eta(\gamma\gamma)$	100.0	10.0	15.5%	8	1.7 ± 0.4	11.5	$(3.9\text{–}15) \times 10^{-4}$	<2.9	$1.6 \pm 0.7 \pm 0.2$
$J/\psi\eta(\pi^+\pi^-\pi^0)$	72.0	10.0	8.7%	4	1.5 ± 0.9	6.76	$(0.66\text{–}2.2) \times 10^{-1}$	<5.1	$1.9 \pm 1.7 \pm 0.2$
$J/\psi\eta$ combined							$(2.6\text{–}33) \times 10^{-5}$	<2.7	$1.6 \pm 0.6 \pm 0.1$

m_{ES} are decay mode dependent. A signal region for each mode is defined as a rectangular region in the ΔE versus m_{ES} plane (Table II). The m_{ES} range is given in terms of $m_{\mathrm{ES}} - m_B$, where m_B is the mass of B meson. The number of data events, n_0, observed in the signal region for each mode is listed in Table II.

The efficiencies for each mode are determined by Monte Carlo simulation. The simulations of $J/\psi\phi K$ and $J/\psi\phi$ decays assumed three- and two-body phase space, respectively, with unpolarized J/ψ and ϕ decays. The $J/\psi\eta$ and $J/\psi\eta'$ simulations used the angular correlations determined by the helicity amplitude [11].

The backgrounds in the m_{ES} distribution have two components: a combinatoric background, whose shape is described by an ARGUS function [12], and a peaking background that peaks in the signal region and is described by a Gaussian function. The sources of combinatoric background are the continuum events and two categories of $B\overline{B}$ events: decays with a leptonic J/ψ decay, and those without. Monte Carlo simulation studies show that the source of the peaking background is $B\overline{B}$ events that contain a leptonic J/ψ decay.

The shape of the ARGUS function is determined mode by mode by fitting to a simulated m_{ES} distribution formed from data event candidates using the same selection except negating the normal lepton identification.

The normalization of the combinatoric background for each mode is obtained from a fit to the m_{ES} distributions in the ΔE signal region of the on-peak data. The integral of the ARGUS function in the signal region is n_C, the number of combinatoric background events.

The peaking background is determined from a fit to the m_{ES} distribution of Monte Carlo $B\overline{B}$ events with leptonic J/ψ decays using the sum of a Gaussian and an ARGUS function. The number of peaking background events n_P is the integral of the Gaussian function in the signal region.

The total number of background events (n_b) and the uncertainty on this number (σ_b) listed in Table II are calculated from the fit value of n_C and n_P and their errors. The combinatoric background is by far the dominant background in all modes except the $B^0 \to J/\psi\eta(\pi^+\pi^-\pi^0)$ mode, where the peaking component is $\sim$20% of the total background.

Table III lists the systematic error from the uncertainty on each of the following: $N_{B\overline{B}}$; secondary branching fractions [13]; Monte Carlo statistics; PID, tracking, and photon detection efficiencies, which are based on the study of control samples; and background parametrization, which is estimated using ΔE sideband information.

Additional systematic uncertainties due to the decay model dependence are estimated for the modes $J/\psi\phi$, $J/\psi\phi K^+$, and $J/\psi\phi K^0_S$. Monte Carlo simulations are used to determine how the efficiency depends on assumptions about intermediate resonances and angular distributions. Two samples are generated for each of the three modes with decay distributions determined by the assumed polarization of the vector daughter mesons, rather than by phase space. One sample is generated with 100% transversely polarized J/ψ and ϕ mesons, and the other with 100% longitudinally polarized J/ψ and ϕ mesons. The resulting relative change in efficiency is entered as a

TABLE III. Systematic error summary on the branching fractions. All are fractional uncertainties in percent.

Mode	$N_{B\overline{B}}$	Secondary branching fractions	Monte Carlo statistics	PID, tracking, photon detection	Background parametrization	Model	Total
$J/\psi\phi K^+$	1.1	2.2	1.6	8.2	5.9	0.4	10.4
$J/\psi\phi K^0_S$	1.1	2.2	2.1	8.3	1.9	0.9	9.3
$J/\psi\phi$	1.1	2.2	1.6	6.7	12.0	1.0	14.1
$J/\psi\eta'$	1.1	3.8	4.6	9.3	7.1	···	13.3
$J/\psi\eta(\gamma\gamma)$	1.1	1.8	1.6	6.0	6.9	···	9.5
$J/\psi\eta(\pi^+\pi^-\pi^0)$	1.1	2.4	2.2	7.7	8.0	···	11.6

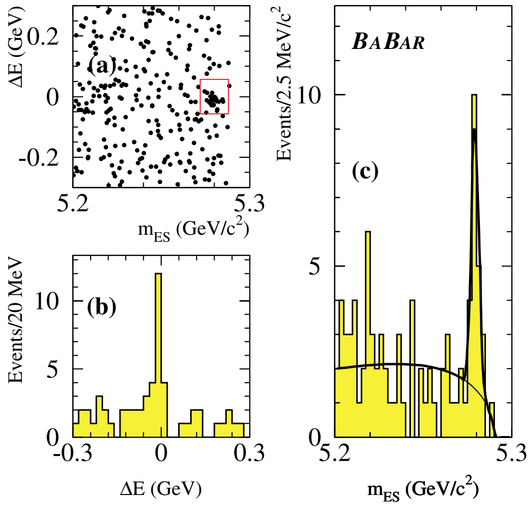

FIG. 2 (color online). The $B^+ \to J/\psi\phi K^+$ mode. The ΔE vs $m_{\rm ES}$ event distribution is shown in (a) with a small rectangle corresponding to the signal region selection defined in Table II. The ΔE projection with a $m_{\rm ES}$ signal region selection is shown in (b). The $m_{\rm ES}$ projection with a ΔE signal region selection is shown in (c). The solid line in (c) is the fit described in the text. The Gaussian component includes both the signal and peaking background.

fractional systematic error in Table III. An additional check based on Monte Carlo samples with an intermediate state gives negligible effect.

The total systematic error for each mode combines all these separate errors in quadrature and is listed (Total) in Table III.

There is evidence for signals in the $J/\psi\phi K^+$ and $J/\psi\phi K^0_S$ modes. The results are shown in Figs. 2 and 3. The branching fraction for these modes is determined by a simple subtraction of events in the signal region that yields the number of signal events, $n_s = n_0 - n_b$. The calculation of the branching fraction is based on the efficiency, n_s, $N_{B\bar{B}}$, and the secondary branching fractions [13] for the J/ψ, ϕ, and K^0_S. Table II includes branching fractions, the statistical and systematic errors, the derived result for $B^0 \to J/\psi\phi K^0$, and the probability for a null hypothesis (P value) which is the Poisson probability that the background fluctuates to n_0 or greater. This probability is calculated using both the central value of our background estimate n_b and the value increased by 1 standard deviation, $n_b + \sigma_b$. This provides an estimate of probability including the background systematic uncertainty.

For modes with no signal or limited statistical evidence ($J/\psi\phi$, $J/\psi\eta$, $J/\psi\eta'$), we determine both a central confidence interval and an upper limit interpretation for the branching fraction. The upper limit method uses n_0, n_b, σ_b, and the total systematic uncertainty σ_T. Assuming the two uncertainties (σ_b, σ_T) are uncorrelated and Gaussian, the Bayesian upper limit on the number of events ($N_{90\%}$) is obtained by folding the Poisson distribution with two normal distributions for these two uncertainties and integrating it to the 90% confidence level (C.L.). This assumes the prior branching fraction distributions are uniform.

In Table II, we list the efficiency, the number of observed events, the expected number of background events, the P value, the 90% C.L. upper limit for observed events, the corresponding branching fraction limit, and a central interval for the branching fraction. The upper limit obtained from the combination of the two $B^0 \to J/\psi\eta$ modes is shown in Table II. We also combine the observed numbers of events for the two $B^0 \to J/\psi\eta$ modes to calculate a branching fraction of $(1.6 \pm 0.6(\text{stat}) \pm 0.1(\text{syst})) \times 10^{-5}$ and the combined probability that the background fluctuates up to the observed number of events or higher is $(2.6\text{–}33) \times 10^{-5}$, where the background is estimated using its central value and a value increased by 1 standard deviation.

In summary, we determine the branching fraction of $B \to J/\psi\phi K$ in two modes, $\mathcal{B}(B^+ \to J/\psi\phi K^+) = (4.4 \pm 1.4 \pm 0.5) \times 10^{-5}$ and $\mathcal{B}(B^0 \to J/\psi\phi K^0_S) = (5.1 \pm 1.9 \pm 0.5) \times 10^{-5}$. The branching fraction of $B \to J/\psi\phi K$ is consistent with and much improved over the CLEO [14] result, $(8.8^{+3.5}_{-3.0} \pm 1.3) \times 10^{-5}$. Upper limits have been determined for the modes $B^0 \to J/\psi\phi$, $J/\psi\eta$, and $J/\psi\eta'$. The $B^0 \to J/\psi\eta$ search is significantly more sensitive than the L3 Collaboration [15] results which set a limit of $<1.2 \times 10^{-3}$ at 90% C.L. In addition, the branching fraction from the combined $B^0 \to J/\psi\eta$ modes is comparable to the $B^0 \to J/\psi\pi^0$ branching fraction [3]. Finally, the search and resulting branching fraction upper limits for $B^0 \to J/\psi\eta'$ and $B^0 \to J/\psi\phi$ are presented.

We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues, and

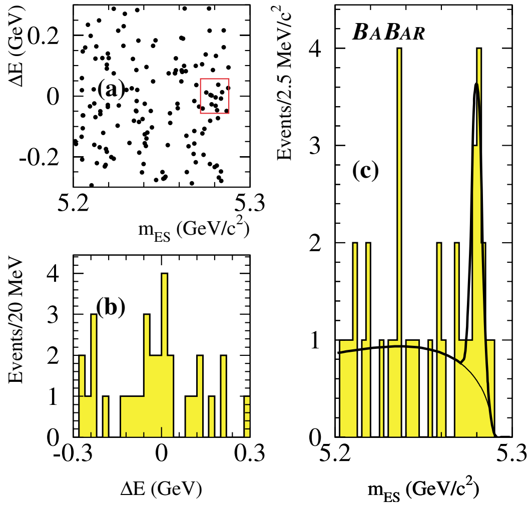

FIG. 3 (color online). The $B^0 \to J/\psi\phi K^0_S$ mode. The descriptions of (a), (b), and (c) follow those of Figs. 2(a)–2(c), respectively.

for the substantial dedicated effort from the computing organizations that support *BABAR*. The collaborating institutions wish to thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (U.S.A.), NSERC (Canada), IHEP (China), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), NFR (Norway), MIST (Russia), and PPARC (United Kingdom). Individuals have received support from the A. P. Sloan Foundation, Research Corporation, and Alexander von Humboldt Foundation.

---

*Also with Università di Perugia, I-06100 Perugia, Italy.

[1] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **86**, 2515 (2001); B. Aubert *et al.*, Phys. Rev. Lett. **87**, 91801 (2001); B. Aubert *et al.*, Phys. Rev. D **66**, 32003 (2002); Belle Collaboration, K. Abe *et al.*, Phys. Rev. Lett. **86**, 2509 (2001); K. Abe *et al.*, Phys. Rev. Lett. **87**, 91802 (2001); K. Abe *et al.*, Phys. Rev. D **66**, 71102 (2002).

[2] N. Cabibbo, Phys. Rev. Lett. **10**, 531 (1963); M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).

[3] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. D **65**, 32001 (2002). This publication forms a basic reference for our analysis. The helicity angles and thrust variable are described in section VII.C.1, the ARGUS function and beam energy-substituted mass in section VII.C, and the particle identification and tracking criteria for the photons, electrons, and muons in sections V.C and V.D.

[4] CLEO Collaboration, M. Bishai *et al.*, Phys. Lett. B **369**, 186 (1996); *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **90**, 91801 (2003).

[5] M. Beneke, G. Buchalla, and I. Dunietz, Phys. Lett. B **393**, 132 (1997).

[6] A. Deandrea *et al.*, Phys. Lett. B **318**, 549 (1993).

[7] F. E. Close *et al.*, Phys. Rev. D **57**, 5653 (1998).

[8] *BABAR* Collaboration, B. Aubert *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **479**, 1 (2002).

[9] The particle identification selection is taken from Ref. [3], where the electron candidates are required to satisfy combinations of "Loose" and "VeryTight" selections, the muon candidates use combinations of "VeryLoose," "Loose," and "VeryTight" selections, and the photon candidates use the same photon selections described in sections V.B and V.C.

[10] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. D **66**, 32003 (2002). The charged kaon candidate not from ϕ decay will be vetoed if it satisfies the "loose pion" selection, whereas the kaon candidates from the ϕ decay use a selection slightly more stringent than the "VeryLoose" selection as described in this reference in section II.D.3.

[11] M. Jacob and G. C. Wick, Ann. Phys. (Paris) **7**, 404 (1959); A. D. Martin and T. D. Spearman, *Elementary Particle Physics* (North-Holland, Amsterdam, 1970).

[12] ARGUS Collaboration, H. Albrecht *et al.*, Z. Phys. C **48**, 543 (1990).

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

[14] CLEO Collaboration, A. Anastassov *et al.*, Phys. Rev. Lett. **84**, 1393 (2000).

[15] L3 Collaboration, M. Acciarri *et al.*, Phys. Lett. B **391**, 481 (1997).