Vector-Tensor and Vector-Vector Decay Amplitude Analysis of $B^0 \to \varphi K^{*0}$

B. Aubert,[1] M. Bona,[1] D. Boutigny,[1] F. Couderc,[1] Y. Karyotakis,[1] J. P. Lees,[1] V. Poireau,[1] V. Tisserand,[1] A. Zghiche,[1]
E. Grauges,[2] A. Palano,[3] J. C. Chen,[4] N. D. Qi,[4] G. Rong,[4] P. Wang,[4] Y. S. Zhu,[4] G. Eigen,[5] I. Ofte,[5] B. Stugu,[5]
G. S. Abrams,[6] M. Battaglia,[6] D. N. Brown,[6] J. Button-Shafer,[6] R. N. Cahn,[6] E. Charles,[6] M. S. Gill,[6] Y. Groysman,[6]
R. G. Jacobsen,[6] J. A. Kadyk,[6] L. T. Kerth,[6] Yu. G. Kolomensky,[6] G. Kukartsev,[6] D. Lopes Pegna,[6] G. Lynch,[6] L. M. Mir,[6]
T. J. Orimoto,[6] M. Pripstein,[6] N. A. Roe,[6] M. T. Ronan,[6] W. A. Wenzel,[6] P. del Amo Sanchez,[7] M. Barrett,[7] K. E. Ford,[7]
T. J. Harrison,[7] A. J. Hart,[7] C. M. Hawkes,[7] A. T. Watson,[7] T. Held,[8] H. Koch,[8] B. Lewandowski,[8] M. Pelizaeus,[8] K. Peters,[8]
T. Schroeder,[8] M. Steinke,[8] J. T. Boyd,[9] J. P. Burke,[9] W. N. Cottingham,[9] D. Walker,[9] D. J. Asgeirsson,[10]
T. Cuhadar-Donszelmann,[10] B. G. Fulsom,[10] C. Hearty,[10] N. S. Knecht,[10] T. S. Mattison,[10] J. A. McKenna,[10] A. Khan,[11]
P. Kyberd,[11] M. Saleem,[11] D. J. Sherwood,[11] L. Teodorescu,[11] V. E. Blinov,[12] A. D. Bukin,[12] V. P. Druzhinin,[12]
V. B. Golubev,[12] A. P. Onuchin,[12] S. I. Serednyakov,[12] Yu. I. Skovpen,[12] E. P. Solodov,[12] K. Yu Todyshev,[12] D. S. Best,[13]
M. Bondioli,[13] M. Bruinsma,[13] M. Chao,[13] S. Curry,[13] I. Eschrich,[13] D. Kirkby,[13] A. J. Lankford,[13] P. Lund,[13]
M. Mandelkern,[13] W. Roethel,[13] D. P. Stoker,[13] S. Abachi,[14] C. Buchanan,[14] S. D. Foulkes,[15] J. W. Gary,[15] O. Long,[15]
B. C. Shen,[15] K. Wang,[15] L. Zhang,[15] H. K. Hadavand,[16] E. J. Hill,[16] H. P. Paar,[16] S. Rahatlou,[16] V. Sharma,[16]
J. W. Berryhill,[17] C. Campagnari,[17] A. Cunha,[17] B. Dahmes,[17] T. M. Hong,[17] D. Kovalskyi,[17] J. D. Richman,[17]
T. W. Beck,[18] A. M. Eisner,[18] C. J. Flacco,[18] C. A. Heusch,[18] J. Kroseberg,[18] W. S. Lockman,[18] G. Nesom,[18] T. Schalk,[18]
B. A. Schumm,[18] A. Seiden,[18] P. Spradlin,[18] D. C. Williams,[18] M. G. Wilson,[18] J. Albert,[19] E. Chen,[19] C. H. Cheng,[19]
A. Dvoretskii,[19] F. Fang,[19] D. G. Hitlin,[19] I. Narsky,[19] T. Piatenko,[19] F. C. Porter,[19] G. Mancinelli,[20] B. T. Meadows,[20]
K. Mishra,[20] M. D. Sokoloff,[20] F. Blanc,[21] P. C. Bloom,[21] S. Chen,[21] W. T. Ford,[21] J. F. Hirschauer,[21] A. Kreisel,[21]
M. Nagel,[21] U. Nauenberg,[21] A. Olivas,[21] W. O. Ruddick,[21] J. G. Smith,[21] K. A. Ulmer,[21] S. R. Wagner,[21] J. Zhang,[21]
A. Chen,[22] E. A. Eckhart,[22] A. Soffer,[22] W. H. Toki,[22] R. J. Wilson,[22] F. Winklmeier,[22] Q. Zeng,[22] D. D. Altenburg,[23]
E. Feltresi,[23] A. Hauke,[23] H. Jasper,[23] J. Merkel,[23] A. Petzold,[23] B. Spaan,[23] T. Brandt,[24] V. Klose,[24] H. M. Lacker,[24]
W. F. Mader,[24] R. Nogowski,[24] J. Schubert,[24] K. R. Schubert,[24] R. Schwierz,[24] J. E. Sundermann,[24] A. Volk,[24]
D. Bernard,[25] G. R. Bonneaud,[25] E. Latour,[25] Ch. Thiebaux,[25] M. Verderi,[25] P. J. Clark,[26] W. Gradl,[26] F. Muheim,[26]
S. Playfer,[26] A. I. Robertson,[26] Y. Xie,[26] M. Andreotti,[27] D. Bettoni,[27] C. Bozzi,[27] R. Calabrese,[27] G. Cibinetto,[27]
E. Luppi,[27] M. Negrini,[27] A. Petrella,[27] L. Piemontese,[27] E. Prencipe,[27] F. Anulli,[28] R. Baldini-Ferroli,[28] A. Calcaterra,[28]
R. de Sangro,[28] G. Finocchiaro,[28] S. Pacetti,[28] P. Patteri,[28] I. M. Peruzzi,[28,*] M. Piccolo,[28] M. Rama,[28] A. Zallo,[28]
A. Buzzo,[29] R. Contri,[29] M. Lo Vetere,[29] M. M. Macri,[29] M. R. Monge,[29] S. Passaggio,[29] C. Patrignani,[29] E. Robutti,[29]
A. Santroni,[29] S. Tosi,[29] G. Brandenburg,[30] K. S. Chaisanguanthum,[30] C. L. Lee,[30] M. Morii,[30] J. Wu,[30] R. S. Dubitzky,[31]
J. Marks,[31] S. Schenk,[31] U. Uwer,[31] D. J. Bard,[32] W. Bhimji,[32] D. A. Bowerman,[32] P. D. Dauncey,[32] U. Egede,[32]
R. L. Flack,[32] J. A. Nash,[32] M. B. Nikolich,[32] W. Panduro Vazquez,[32] P. K. Behera,[33] X. Chai,[33] M. J. Charles,[33]
U. Mallik,[33] N. T. Meyer,[33] V. Ziegler,[33] J. Cochran,[34] H. B. Crawley,[34] L. Dong,[34] V. Eyges,[34] W. T. Meyer,[34] S. Prell,[34]
E. I. Rosenberg,[34] A. E. Rubin,[34] Y. Gao,[35] A. V. Gritsan,[35] Z. J. Guo,[35] A. G. Denig,[36] M. Fritsch,[36] G. Schott,[36]
N. Arnaud,[37] M. Davier,[37] G. Grosdidier,[37] A. Höcker,[37] V. Lepeltier,[37] F. Le Diberder,[37] A. M. Lutz,[37] A. Oyanguren,[37]
S. Pruvot,[37] S. Rodier,[37] P. Roudeau,[37] M. H. Schune,[37] J. Serrano,[37] A. Stocchi,[37] W. F. Wang,[37] G. Wormser,[37]
D. J. Lange,[38] D. M. Wright,[38] C. A. Chavez,[39] I. J. Forster,[39] J. R. Fry,[39] E. Gabathuler,[39] R. Gamet,[39] K. A. George,[39]
D. E. Hutchcroft,[39] D. J. Payne,[39] K. C. Schofield,[39] C. Touramanis,[39] A. J. Bevan,[40] C. K. Clarke,[40] F. Di Lodovico,[40]
W. Menges,[40] R. Sacco,[40] G. Cowan,[41] H. U. Flaecher,[41] D. A. Hopkins,[41] P. S. Jackson,[41] T. R. McMahon,[41]
F. Salvatore,[41] A. C. Wren,[41] D. N. Brown,[42] C. L. Davis,[42] J. Allison,[43] N. R. Barlow,[43] R. J. Barlow,[43] Y. M. Chia,[43]
C. L. Edgar,[43] G. D. Lafferty,[43] M. T. Naisbit,[43] J. C. Williams,[43] J. I. Yi,[43] C. Chen,[44] W. D. Hulsbergen,[44] A. Jawahery,[44]
C. K. Lae,[44] D. A. Roberts,[44] G. Simi,[44] G. Blaylock,[45] C. Dallapiccola,[45] S. S. Hertzbach,[45] X. Li,[45] T. B. Moore,[45]
S. Saremi,[45] H. Staengle,[45] R. Cowan,[46] G. Sciolla,[46] S. J. Sekula,[46] M. Spitznagel,[46] F. Taylor,[46] R. K. Yamamoto,[46]
H. Kim,[47] S. E. Mclachlin,[47] P. .M. Patel,[47] S. H. Robertson,[47] A. Lazzaro,[48] V. Lombardo,[48] F. Palombo,[48] J. M. Bauer,[49]
L. Cremaldi,[49] V. Eschenburg,[49] R. Godang,[49] R. Kroeger,[49] D. A. Sanders,[49] D. J. Summers,[49] H. W. Zhao,[49] S. Brunet,[50]
D. Côté,[50] M. Simard,[50] P. Taras,[50] F. B. Viaud,[50] H. Nicholson,[51] N. Cavallo,[52,†] G. De Nardo,[52] F. Fabozzi,[52,†] C. Gatto,[52]
L. Lista,[52] D. Monorchio,[52] P. Paolucci,[52] D. Piccolo,[52] C. Sciacca,[52] M. A. Baak,[53] G. Raven,[53] H. L. Snoek,[53]
C. P. Jessop,[54] J. M. LoSecco,[54] G. Benelli,[55] L. A. Corwin,[55] K. K. Gan,[55] K. Honscheid,[55] D. Hufnagel,[55] P. D. Jackson,[55]
H. Kagan,[55] R. Kass,[55] A. M. Rahimi,[55] J. J. Regensburger,[55] R. Ter-Antonyan,[55] Q. K. Wong,[55] N. L. Blount,[56] J. Brau,[56]
R. Frey,[56] O. Igonkina,[56] J. A. Kolb,[56] M. Lu,[56] C. T. Potter,[56] R. Rahmat,[56] N. B. Sinev,[56] D. Strom,[56] J. Strube,[56]

E. Torrence,[56] A. Gaz,[57] M. Margoni,[57] M. Morandin,[57] A. Pompili,[57] M. Posocco,[57] M. Rotondo,[57] F. Simonetto,[57]
R. Stroili,[57] C. Voci,[57] M. Benayoun,[58] H. Briand,[58] J. Chauveau,[58] P. David,[58] L. Del Buono,[58] Ch. de la Vaissière,[58]
O. Hamon,[58] B. L. Hartfiel,[58] Ph. Leruste,[58] J. Malclès,[58] J. Ocariz,[58] L. Roos,[58] G. Therin,[58] L. Gladney,[59] M. Biasini,[60]
R. Covarelli,[60] C. Angelini,[61] G. Batignani,[61] S. Bettarini,[61] F. Bucci,[61] G. Calderini,[61] M. Carpinelli,[61] R. Cenci,[61]
F. Forti,[61] M. A. Giorgi,[61] A. Lusiani,[61] G. Marchiori,[61] M. A. Mazur,[61] M. Morganti,[61] N. Neri,[61] E. Paoloni,[61] G. Rizzo,[61]
J. J. Walsh,[61] M. Haire,[62] D. Judd,[62] D. E. Wagoner,[62] J. Biesiada,[63] N. Danielson,[63] P. Elmer,[63] Y. P. Lau,[63] C. Lu,[63]
J. Olsen,[63] A. J. S. Smith,[63] A. V. Telnov,[63] F. Bellini,[64] G. Cavoto,[64] A. D'Orazio,[64] D. del Re,[64] E. Di Marco,[64]
R. Faccini,[64] F. Ferrarotto,[64] F. Ferroni,[64] M. Gaspero,[64] L. Li Gioi,[64] M. A. Mazzoni,[64] S. Morganti,[64] G. Piredda,[64]
F. Polci,[64] F. Safai Tehrani,[64] C. Voena,[64] M. Ebert,[65] H. Schröder,[65] R. Waldi,[65] T. Adye,[66] B. Franek,[66] E. O. Olaiya,[66]
S. Ricciardi,[66] F. F. Wilson,[66] R. Aleksan,[67] S. Emery,[67] A. Gaidot,[67] S. F. Ganzhur,[67] G. Hamel de Monchenault,[67]
W. Kozanecki,[67] M. Legendre,[67] G. Vasseur,[67] Ch. Yèche,[67] M. Zito,[67] X. R. Chen,[68] H. Liu,[68] W. Park,[68] M. V. Purohit,[68]
J. R. Wilson,[68] M. T. Allen,[69] D. Aston,[69] R. Bartoldus,[69] P. Bechtle,[69] N. Berger,[69] R. Claus,[69] J. P. Coleman,[69]
M. R. Convery,[69] J. C. Dingfelder,[69] J. Dorfan,[69] G. P. Dubois-Felsmann,[69] D. Dujmic,[69] W. Dunwoodie,[69] R. C. Field,[69]
T. Glanzman,[69] S. J. Gowdy,[69] M. T. Graham,[69] P. Grenier,[69] V. Halyo,[69] C. Hast,[69] T. Hryn'ova,[69] W. R. Innes,[69]
M. H. Kelsey,[69] P. Kim,[69] D. W. G. S. Leith,[69] S. Li,[69] S. Luitz,[69] V. Luth,[69] H. L. Lynch,[69] D. B. MacFarlane,[69]
H. Marsiske,[69] R. Messner,[69] D. R. Muller,[69] C. P. O'Grady,[69] V. E. Ozcan,[69] A. Perazzo,[69] M. Perl,[69] T. Pulliam,[69]
B. N. Ratcliff,[69] A. Roodman,[69] A. A. Salnikov,[69] R. H. Schindler,[69] J. Schwiening,[69] A. Snyder,[69] J. Stelzer,[69] D. Su,[69]
M. K. Sullivan,[69] K. Suzuki,[69] S. K. Swain,[69] J. M. Thompson,[69] J. Va'vra,[69] N. van Bakel,[69] A. P. Wagner,[69] M. Weaver,[69]
A. J. R. Weinstein,[69] W. J. Wisniewski,[69] M. Wittgen,[69] D. H. Wright,[69] H. W. Wulsin,[69] A. K. Yarritu,[69] K. Yi,[69]
C. C. Young,[69] P. R. Burchat,[70] A. J. Edwards,[70] S. A. Majewski,[70] B. A. Petersen,[70] L. Wilden,[70] S. Ahmed,[71]
M. S. Alam,[71] R. Bula,[71] J. A. Ernst,[71] V. Jain,[71] B. Pan,[71] M. A. Saeed,[71] F. R. Wappler,[71] S. B. Zain,[71] W. Bugg,[72]
M. Krishnamurthy,[72] S. M. Spanier,[72] R. Eckmann,[73] J. L. Ritchie,[73] A. Satpathy,[73] C. J. Schilling,[73] R. F. Schwitters,[73]
J. M. Izen,[74] X. C. Lou,[74] S. Ye,[74] F. Bianchi,[75] F. Gallo,[75] D. Gamba,[75] M. Bomben,[76] L. Bosisio,[76] C. Cartaro,[76]
F. Cossutti,[76] G. Della Ricca,[76] S. Dittongo,[76] L. Lanceri,[76] L. Vitale,[76] V. Azzolini,[77] N. Lopez-March,[77]
F. Martinez-Vidal,[77] Sw. Banerjee,[78] B. Bhuyan,[78] C. M. Brown,[78] D. Fortin,[78] K. Hamano,[78] R. Kowalewski,[78]
I. M. Nugent,[78] J. M. Roney,[78] R. J. Sobie,[78] J. J. Back,[79] P. F. Harrison,[79] T. E. Latham,[79] G. B. Mohanty,[79]
M. Pappagallo,[79,‡] H. R. Band,[80] X. Chen,[80] B. Cheng,[80] S. Dasu,[80] M. Datta,[80] K. T. Flood,[80] J. J. Hollar,[80] P. E. Kutter,[80]
B. Mellado,[80] A. Mihalyi,[80] Y. Pan,[80] M. Pierini,[80] R. Prepost,[80] S. L. Wu,[80] Z. Yu,[80] and H. Neal[81]

(The *BABAR* Collaboration)

[1]*Laboratoire de Physique des Particules, IN2P3/CNRS et Université de Savoie, F-74941 Annecy-Le-Vieux, France*
[2]*Universitat de Barcelona, Facultat de Fisica, Departament ECM, E-08028 Barcelona, Spain*
[3]*Università di Bari, Dipartimento di Fisica and INFN, I-70126 Bari, Italy*
[4]*Institute of High Energy Physics, Beijing 100039, China*
[5]*University of Bergen, Institute of Physics, N-5007 Bergen, Norway*
[6]*Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA*
[7]*University of Birmingham, Birmingham, B15 2TT, United Kingdom*
[8]*Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany*
[9]*University of Bristol, Bristol BS8 1TL, United Kingdom*
[10]*University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1*
[11]*Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom*
[12]*Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia*
[13]*University of California at Irvine, Irvine, California 92697, USA*
[14]*University of California at Los Angeles, Los Angeles, California 90024, USA*
[15]*University of California at Riverside, Riverside, California 92521, USA*
[16]*University of California at San Diego, La Jolla, California 92093, USA*
[17]*University of California at Santa Barbara, Santa Barbara, California 93106, USA*
[18]*University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA*
[19]*California Institute of Technology, Pasadena, California 91125, USA*
[20]*University of Cincinnati, Cincinnati, Ohio 45221, USA*
[21]*University of Colorado, Boulder, Colorado 80309, USA*
[22]*Colorado State University, Fort Collins, Colorado 80523, USA*
[23]*Universität Dortmund, Institut für Physik, D-44221 Dortmund, Germany*
[24]*Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany*

[25]Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, F-91128 Palaiseau, France

[26]University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom

[27]Università di Ferrara, Dipartimento di Fisica and INFN, I-44100 Ferrara, Italy

[28]Laboratori Nazionali di Frascati dell'INFN, I-00044 Frascati, Italy

[29]Università di Genova, Dipartimento di Fisica and INFN, I-16146 Genova, Italy

[30]Harvard University, Cambridge, Massachusetts 02138, USA

[31]Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany

[32]Imperial College London, London, SW7 2AZ, United Kingdom

[33]University of Iowa, Iowa City, Iowa 52242, USA

[34]Iowa State University, Ames, Iowa 50011-3160, USA

[35]Johns Hopkins University, Baltimore, Maryland 21218, USA

[36]Universität Karlsruhe, Institut für Experimentelle Kernphysik, D-76021 Karlsruhe, Germany

[37]Laboratoire de l'Accélérateur Linéaire, IN2P3/CNRS et Université Paris-Sud 11, Centre Scientifique d'Orsay,
B.P. 34, F-91898 ORSAY Cedex, France

[38]Lawrence Livermore National Laboratory, Livermore, California 94550, USA

[39]University of Liverpool, Liverpool L69 7ZE, United Kingdom

[40]Queen Mary, University of London, E1 4NS, United Kingdom

[41]University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom

[42]University of Louisville, Louisville, Kentucky 40292, USA

[43]University of Manchester, Manchester M13 9PL, United Kingdom

[44]University of Maryland, College Park, Maryland 20742, USA

[45]University of Massachusetts, Amherst, Massachusetts 01003, USA

[46]Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA

[47]McGill University, Montréal, Québec, Canada H3A 2T8

[48]Università di Milano, Dipartimento di Fisica and INFN, I-20133 Milano, Italy

[49]University of Mississippi, University, Mississippi 38677, USA

[50]Université de Montréal, Physique des Particules, Montréal, Québec, Canada H3C 3J7

[51]Mount Holyoke College, South Hadley, Massachusetts 01075, USA

[52]Università di Napoli Federico II, Dipartimento di Scienze Fisiche and INFN, I-80126, Napoli, Italy

[53]NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands

[54]University of Notre Dame, Notre Dame, Indiana 46556, USA

[55]Ohio State University, Columbus, Ohio 43210, USA

[56]University of Oregon, Eugene, Oregon 97403, USA

[57]Università di Padova, Dipartimento di Fisica and INFN, I-35131 Padova, Italy

[58]Laboratoire de Physique Nucléaire et de Hautes Energies, IN2P3/CNRS, Université Pierre et Marie Curie-Paris6,
Université Denis Diderot-Paris7, F-75252 Paris, France

[59]University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA

[60]Università di Perugia, Dipartimento di Fisica and INFN, I-06100 Perugia, Italy

[61]Università di Pisa, Dipartimento di Fisica, Scuola Normale Superiore and INFN, I-56127 Pisa, Italy

[62]Prairie View A&M University, Prairie View, Texas 77446, USA

[63]Princeton University, Princeton, New Jersey 08544, USA

[64]Università di Roma La Sapienza, Dipartimento di Fisica and INFN, I-00185 Roma, Italy

[65]Universität Rostock, D-18051 Rostock, Germany

[66]Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom

[67]DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France

[68]University of South Carolina, Columbia, South Carolina 29208, USA

[69]Stanford Linear Accelerator Center, Stanford, California 94309, USA

[70]Stanford University, Stanford, California 94305-4060, USA

[71]State University of New York, Albany, New York 12222, USA

[72]University of Tennessee, Knoxville, Tennessee 37996, USA

[73]University of Texas at Austin, Austin, Texas 78712, USA

[74]University of Texas at Dallas, Richardson, Texas 75083, USA

[75]Università di Torino, Dipartimento di Fisica Sperimentale and INFN, I-10125 Torino, Italy

[76]Università di Trieste, Dipartimento di Fisica and INFN, I-34127 Trieste, Italy

[77]IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain

[78]University of Victoria, Victoria, British Columbia, Canada V8W 3P6

[79]Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom

[80]University of Wisconsin, Madison, Wisconsin 53706, USA

[81]Yale University, New Haven, Connecticut 06511, USA

We perform an amplitude analysis of the decays $B^0 \to \phi K_2^*(1430)^0$, $\phi K^*(892)^0$, and $\phi(K\pi)_{S\text{-wave}}^0$ with a sample of about 384×10^6 $B\bar{B}$ pairs recorded with the *BABAR* detector. The fractions of longitudinal polarization f_L of the vector-tensor and vector-vector decay modes are measured to be $0.853^{+0.061}_{-0.069} \pm 0.036$ and $0.506 \pm 0.040 \pm 0.015$, respectively. Overall, twelve parameters are measured for the vector-vector decay and seven parameters for the vector-tensor decay, including the branching fractions and parameters sensitive to *CP* violation.

The interest in the polarization and *CP*-asymmetry measurements in $B \to \phi K^*$ decays is motivated by their potential sensitivity to physics beyond the standard model in the $b \to s$ transition, shown in Fig. 1(a) [1]. The polarization measurements of *B* meson decays reveal both strong and weak interaction dynamics and are discussed in a recent review [2,3]. The large fraction of transverse polarization in the $B \to \phi K^*(892)$ decay measured by *BABAR* [4] and by Belle [5] indicates a significant departure from the naive expectation of predominant longitudinal polarization. This suggests other contributions to the decay amplitude, previously neglected, either within or beyond the standard model [6].

We now extend our investigation of the polarization puzzle with an amplitude analysis of the vector-tensor $B^0 \to \phi K_2^*(1430)^0$ decay. We also measure vector-vector $B^0 \to \phi K^*(892)^0$ and vector-scalar $B^0 \to \phi(K\pi)_0^{*0}$ decay amplitudes, where $(K\pi)_0^{*0}$ is the $J^P = 0^+$ $K\pi$ component. We use the dependence on the $K\pi$ invariant mass of the interference between the $J^P = 0^+$ and 1^- or 2^+ components [7,8] to resolve the discrete ambiguity in the determination of the strong and weak phases otherwise present in the $B^0 \to \phi K^*(892)^0$ analysis [2,4,5] and to provide new measurements of the strong and weak phases relative to the vector-scalar decay amplitude.

The angular distribution of the $B \to \phi K^*$ decay can be expressed as a function of $\mathcal{H}_i = \cos\theta_i$ and Φ shown in Fig. 1(b). Here θ_i is the angle between the direction of the K meson from the $K^* \to K\pi$ (θ_1) or $\phi \to K\bar{K}$ (θ_2) and the direction opposite the *B* in the K^* or ϕ rest frame, and Φ is the angle between the decay planes of the two systems. The differential decay width has seven complex amplitudes $A_{J\lambda}$ corresponding to the spin of the $K\pi$ system J and the helicity $\lambda = 0$ or ± 1:

$$\frac{d^3\Gamma}{d\mathcal{H}_1 d\mathcal{H}_2 d\Phi} \propto \left| \sum A_{J\lambda} Y_J^\lambda(\mathcal{H}_1, \Phi) Y_1^{-\lambda}(-\mathcal{H}_2, 0) \right|^2,$$

(1)

where Y_J^λ are the spherical harmonics with $J = 2$ for $K_2^*(1430)$, $J = 1$ for $K^*(892)$, and $J = 0$ for $(K\pi)_0^*$. We can reparameterize the amplitudes with the index J suppressed as A_0 and $A_{\pm 1} = (A_\parallel \pm A_\perp)/\sqrt{2}$.

We analyze $\overset{(-)}{B^0} \to \phi \overset{(-)}{K^{*0}} \to (K^+K^-)(K^\pm\pi^\mp)$ candidates using data collected with the *BABAR* detector [9] at the PEP-II e^+e^- collider. A sample of 383.6 ± 4.2 million

$\Upsilon(4S) \to B\bar{B}$ events was recorded at the center-of-mass energy $\sqrt{s} = 10.58$ GeV. Charged-particle momenta are measured in a tracking system consisting of a silicon vertex tracker with five double-sided layers and a 40-layer drift chamber, both within the 1.5-T magnetic field of a solenoid. Charged-particle identification is provided by measurements of the energy loss in the tracking devices and by a ring-imaging Cherenkov detector.

We use two kinematic variables: $\Delta E = (E_i E_B - \mathbf{p}_i \cdot \mathbf{p}_B - s/2)/\sqrt{s}$ and $m_{\text{ES}} = [(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - \mathbf{p}_B^2]^{1/2}$, where $(E_i, \mathbf{p}_i)$ is the e^+e^- beam four-momentum, and $(E_B, \mathbf{p}_B)$ is the four-momentum of the *B* candidate. We require $|\Delta E| < 0.1$ GeV and $m_{\text{ES}} > 5.25$ GeV. The requirements on the invariant masses are $0.99 < m_{K\bar{K}} < 1.05$ GeV and $0.75 < m_{K\pi} < 1.05$ GeV (lower $m_{K\pi}$ range) or $1.13 < m_{K\pi} < 1.53$ GeV (higher $m_{K\pi}$ range).

To reject the dominant $e^+e^- \to$ quark-antiquark background, we use variables calculated in the center-of-mass frame. We require $|\cos\theta_T| < 0.8$, where θ_T is the angle between the *B*-candidate thrust axis and that of the rest of the event. We construct a Fisher discriminant, $\mathcal{F}$, that combines the polar angles of the *B*-momentum vector and the *B*-candidate thrust axis with respect to the beam axis, and the two Legendre moments L_0 and L_2 of the energy flow around the *B*-candidate thrust axis [10].

We remove signal candidates that have decay products with invariant mass within 12 MeV of the nominal mass values for $D_s^\pm$ or $D^\pm \to \phi\pi^\pm$. In about 5% of events, more than one candidate is reconstructed, and we select the one whose four-track vertex has the lowest χ^2. We define the flavor sign Q to be the charge of the pion.

We use an unbinned, extended maximum-likelihood fit [4] to extract the event yields n_j, flavor asymmetries $\mathcal{A}_j$, and the probability density function (PDF) parameters,
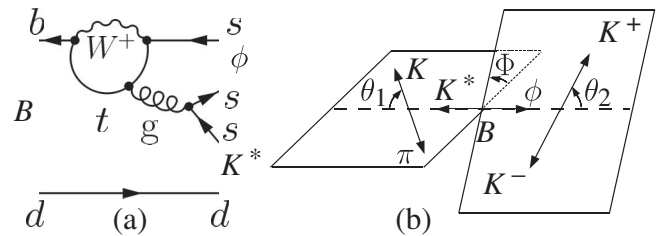

FIG. 1.   (a) Feynman diagram describing the $B^0 \to \phi K^{*0}$ decay; (b) definition of decay angles given in the rest frames of the decaying parents.

denoted by ζ for the polarization parameters and ξ for the remaining parameters. The data model has five event categories j: $B \rightarrow \phi(K\pi)_{J=0,1,2}$, $B \rightarrow f_0(980)K^*$, and combinatorial background. The combinatorial background PDF is found to account well for both the dominant quark-antiquark background and the random tracks from the B decays. The likelihood $\mathcal{L}_i$ for each candidate i is defined as $\mathcal{L}_i = \sum_{j,k} n_j^k \mathcal{P}_j^k(x_i; \zeta; \xi)$, where each of the $\mathcal{P}_j^k$ is the PDF for variables $x_i = \{\mathcal{H}_1, \mathcal{H}_2, \Phi, m_{K\pi}, m_{K\bar{K}}, \Delta E, m_{ES}, \mathcal{F}, Q\}$. The flavor index k corresponds to the value of Q, that is $\mathcal{P}_j^k \equiv \mathcal{P}_j \times \delta_{kQ}$.

We define $n_j = n_j^+ + n_j^-$ and $\mathcal{A}_j = (n_j^+ - n_j^-)/(n_j^+ + n_j^-)$. The polarization parameters, with the index J suppressed, are defined as $f_L = |A_0|^2/\Sigma|A_\lambda|^2$, $f_\perp = |A_\perp|^2/\Sigma|A_\lambda|^2$, $\phi_\parallel = \arg(A_\parallel/A_0)$, and $\phi_\perp = \arg(A_\perp/A_0)$. We allow for CP-violating differences between the $\bar{B}^0$ ($Q = +1$) and B^0 ($Q = -1$) decay amplitudes ($\bar{A}$ and A) and incorporate them via the replacements $f_L \rightarrow f_L \times (1 + \mathcal{A}_{CP}^0 \times Q)$, $f_\perp \rightarrow f_\perp \times (1 + \mathcal{A}_{CP}^\perp \times Q)$, $\phi_\parallel \rightarrow (\phi_\parallel + \Delta\phi_\parallel \times Q)$, and $\phi_\perp \rightarrow (\phi_\perp + \pi/2 + (\Delta\phi_\perp + \pi/2) \times Q)$ [2].

The PDF $\mathcal{P}_j(x_i; \zeta; \xi)$ for a given candidate i is a joint PDF for the helicity angles, resonance masses, and Q, and the product of the PDFs for each of the remaining variables. The helicity part of the exclusive B decay PDF is the ideal angular distribution from Eq. (1), where the amplitudes $A_{J\lambda}$ are expressed in terms of the polarization parameters ζ, multiplied by an empirically-determined acceptance function $\mathcal{G}(\mathcal{H}_1, \mathcal{H}_2, \Phi) \equiv \mathcal{G}_1(\mathcal{H}_1) \times \mathcal{G}_2(\mathcal{H}_2)$. A relativistic J-spin Breit-Wigner amplitude parameterization is used for the resonance mass [3,11], except for the $(K\pi)_0^{*0}$ $m_{K\pi}$ amplitude parameterized with the LASS function [7]. The latter includes the $K_0^*(1430)^0$ resonance together with a nonresonant component.

The interference between the $J = 1$ or 2 and the S-wave $(K\pi)$ contributions is modeled with the three terms $2\mathcal{R}e(A_{J\lambda}A_{00}^*)$ in Eq. (1) with the four-dimensional angular and $m_{K\pi}$ dependence. It has been shown in the decays $B^0 \rightarrow J/\psi(K\pi)_0^{*0}$ and $B^+ \rightarrow \pi^+(K\pi)_0^{*0}$ [8] that the amplitude behavior is consistent with that observed by LASS except for a constant phase shift. We allow an unconstrained overall shift, again with the index J suppressed, $(\delta_0 + \Delta\delta_0 \times Q)$ between the LASS amplitude phase and either the vector ($J = 1$) or the tensor ($J = 2$) resonance amplitude phase.

The parameters ξ describe the background or the remaining signal PDFs. They are left free to vary in the fit for the combinatorial background or are fixed to the values extracted from Monte Carlo (MC) simulation [12] and calibration B-decay channels for the exclusive B decays. We use a sum of Gaussian functions for the parameterization of the signal PDFs for ΔE, m_{ES}, and $\mathcal{F}$. For the combinatorial background, we use polynomials, except for m_{ES} and $\mathcal{F}$ distributions which are parameterized by an empirical phase-space function and by Gaussian func-
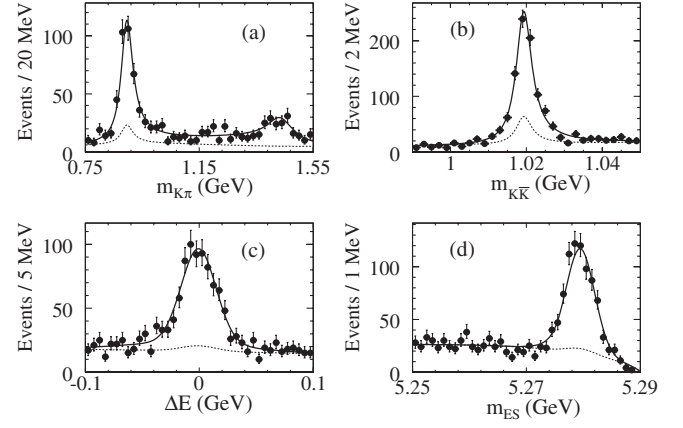

FIG. 2. Projections onto the variables $m_{K\pi}$ (a), $m_{K\bar{K}}$ (b), ΔE (c), and m_{ES} (d) for the signal $B^0 \rightarrow \phi(K\pi)$ candidates. Data distributions are shown with a requirement on the signal-to-background probability ratio calculated with the plotted variable excluded. The solid (dashed) lines show the signal-plus-background (background) PDF projections.

tions, respectively. Resonance production occurs in the background and is taken into account in the PDF.

We observe a nonzero yield with more than 9σ significance, including systematic uncertainties, in each of the three $B^0 \rightarrow \phi K^{*0}$ decay modes. The significance is defined as the square root of the change in $2\ln\mathcal{L}$ when the yield is constrained to zero in the likelihood $\mathcal{L}$. In Figs. 2–4, we show projections onto the variables. In Tables I and II, the n_j, $\mathcal{A}_j$, and $\zeta \equiv \{f_L, f_\perp, \phi_\parallel, \phi_\perp, \delta_0, \mathcal{A}_{CP}^0, \mathcal{A}_{CP}^\perp, \Delta\phi_\parallel, \Delta\phi_\perp, \Delta\delta_0\}$ parameters of the $B^0 \rightarrow \phi K^*(892)^0$ decay or the $\phi K_2^*(1430)^0$ and $\phi(K\pi)_0^{*0}$ decays are obtained from the fit in the lower or higher $m_{K\pi}$ range, respectively.
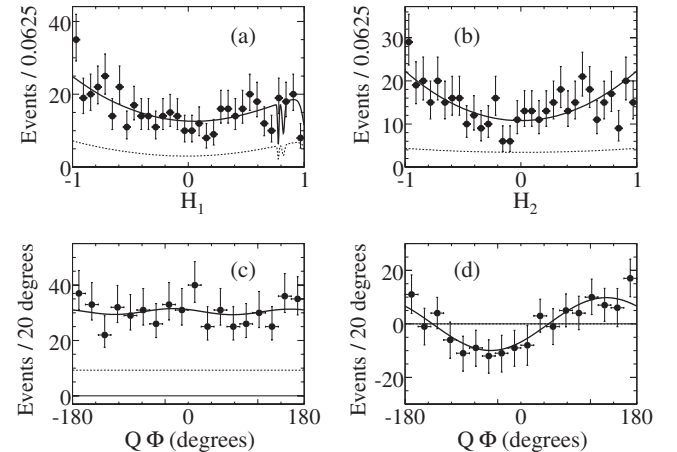

FIG. 3. Projections onto the variables $\mathcal{H}_1$ (a), $\mathcal{H}_2$ (b), $Q\Phi$ (c), and the differences between the $Q\Phi$ projections for events with $\mathcal{H}_1\mathcal{H}_2 > 0$ and with $\mathcal{H}_1\mathcal{H}_2 < 0$ (d) for the signal $B^0 \rightarrow \phi K^*(892)^0$ candidates following the solid (dashed) line definitions in Fig. 2. The $D_{(s)}^\pm$-meson veto causes the sharp acceptance dips seen in (a).
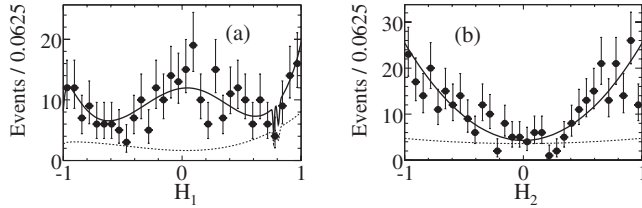
FIG. 4.   Same as Fig. 3(a) and 3(b), but for the signal $B^0 \rightarrow \phi K_2^*(1430)^0$ and $\phi(K\pi)_0^{*0}$ candidates combined.

The nonresonant K^+K^- contribution under the ϕ is accounted for with the $B^0 \rightarrow f_0 K^{*0}$ category. Its yield is consistent with zero in the higher $m_{K\pi}$ range and is 89 ± 18 events in the lower $m_{K\pi}$ range. The uncertainties due to $m_{K\bar{K}}$ interference are estimated with the samples generated according to the observed K^+K^- intensity and with various interference phases analogous to δ_0 in $K\pi$. These are the dominant systematic errors for the ζ parameters of the $B^0 \rightarrow \phi K^*(892)^0$ decay.

We vary those parameters in ξ not used to model combinatoric background within their uncertainties and derive the associated systematic errors. We allow for the flavor-dependent acceptance function and the reconstruction efficiency in the study of asymmetries. The biases from the finite resolution of the angle measurement, the dilution due to the presence of fake combinations, or other imperfections in the signal PDF model are estimated with MC simulation. Additional systematic uncertainty originates from B background, where we estimate that only a few events can fake the signal. The systematic errors in efficiencies are dominated by those in particle identification and track finding. Other systematic effects arise from event-selection criteria, ϕ and K^{*0} branching fractions, and a number of B mesons.

In the lower $m_{K\pi}$ range, the yield of the $\phi(K\pi)_0^{*0}$ contribution is 60^{+17}_{-14} events with the statistical significance of 7.9σ, including the interference term. The dependence of the interference on the $K\pi$ invariant mass [7,8] allows us to reject the other solution near $(2\pi - \phi_\parallel, \pi - \phi_\perp)$ relative to that in Table II for the $B^0 \rightarrow \phi K^*(892)^0$ decay with significance of 5.4σ, including systematic uncertainties.

We also resolve this ambiguity with statistical significance of more than 4σ with the $\bar{B}^0$ or B^0 decays independently. Because of the low significance of our measured $f_\parallel = (1 - f_L - f_\perp)$ (2.9σ) and $f_\perp$ (1.6σ) in the $B^0 \rightarrow \phi K_2^*(1430)^0$ decay, we have insufficient information to constrain $\phi_\parallel$ and $\phi_\perp$ at higher significance and to measure five asymmetries, and so we fix these asymmetry parameters to zero in the fit in the higher $m_{K\pi}$ range.

The $(V - A)$ structure of the weak interactions and the s-quark spin flip suppression in the diagram in Fig. 1(a) suggest $|A_0| \gg |A_{+1}| \gg |A_{-1}|$ [1,6]. This expectation is consistent with our measurements in the vector-tensor $B^0 \rightarrow \phi K_2^*(1430)^0$ decay, but disagrees with our observed vector-vector polarization. In the $B^0 \rightarrow \phi K^*(892)^0$ decay, we obtain the solution $\phi_\parallel \simeq \phi_\perp$ without discrete ambiguities. Combined with the approximate solution $f_L \simeq 1/2$ and $f_\perp \simeq (1 - f_L)/2$, this results in the approximate decay amplitude hierarchy $|A_0| \simeq |A_{+1}| \gg |A_{-1}|$ (and $|\bar{A}_0| \simeq |\bar{A}_{-1}| \gg |\bar{A}_{+1}|$).

We find more than 5σ (4σ) deviation, including systematic uncertainties, of $\phi_\perp(\phi_\parallel)$ from either π or zero in the $B^0 \rightarrow \phi K^*(892)^0$ decay, indicating the presence of final-state interactions (FSI) not accounted for in naive factorization. The effect of FSI is evident in the phase shift of the cosine distribution in Fig. 3(d).

Our measurements of eight CP-violating parameters rule out a significant part of the physical region and are consistent with no CP-violation in this decay. Significant nonzero CP-violating parameters would indicate the presence of new amplitudes with different weak phases. The $\Delta\phi_\perp$ and $\Delta\phi_\parallel$ are particularly interesting due to sensitivity to the weak phases of the amplitudes without hadronic uncertainties [2], such as the relative weak phases of A_{+1} and A_0, while the CP-violating $\Delta\delta_0$ parameter represents potential differences of weak phases among decay modes.

In summary, we have performed an amplitude analysis and searched for CP-violation in the angular distribution with the $B^0 \rightarrow \phi K^{*0}$ decays with the tensor, vector, and scalar K^{*0}. Our results are summarized in Tables I and II and supersede corresponding measurements in Ref. [4]. Our vector-tensor results are in agreement with quark spin flip suppression and A_0 amplitude dominance,

TABLE I.   Fit results for each $m_{K\pi}$ range and signal component: the reconstruction efficiency $\varepsilon_{\text{reco}}$ obtained from MC simulation; the total efficiency ε, including the daughter branching fractions [3]; the number of signal events n_{sig}; statistical significance ($\mathcal{S}$) of the signal; the branching fraction $\mathcal{B}$; and the flavor asymmetry $\mathcal{A}_{CP}$. The branching fraction $\mathcal{B}(B^0 \rightarrow \phi(K\pi)_0^{*0})$ refers to the coherent sum $|A_{\text{res}} + A_{\text{non-res}}|^2$ of resonant and nonresonant $J^P = 0^+$ $K\pi$ components [7] and is quoted for $m_{K\pi} < 1.6$ GeV, while the $\mathcal{B}(B^0 \rightarrow \phi K_0^*(1430)^0)$ is derived from it by integrating separately the Breit-Wigner formula of the resonant $|A_{\text{res}}|^2$ $K\pi$ component [7] without $m_{K\pi}$ restriction. The systematic errors are quoted last.

Mode	$m_{K\pi}$ (GeV)	$m_{K\pi}$ model	$\varepsilon_{\text{reco}}$ (%)	ε (%)	n_{sig} (events)	$\mathcal{S}$ (σ)	$\mathcal{B}$ (10^{-6})	$\mathcal{A}_{CP}$
$\phi K^*(892)^0$	0.75–1.05	Breit-Wigner [3]	35.0 ± 1.7	11.5 ± 0.6	$406 \pm 29 \pm 15$	21.0	$9.2 \pm 0.7 \pm 0.6$	$-0.03 \pm 0.07 \pm 0.03$
$\phi K_2^*(1430)^0$	1.13–1.53	Breit-Wigner [3]	27.1 ± 1.3	4.4 ± 0.2	$133 \pm 19 \pm 7$	9.7	$7.8 \pm 1.1 \pm 0.6$	$-0.12 \pm 0.14 \pm 0.04$
$\phi(K\pi)_0^{*0}$	1.13–1.53	LASS [7]	23.4 ± 1.1	7.7 ± 0.3	$147 \pm 23 \pm 7$	9.8	$5.0 \pm 0.8 \pm 0.3$	$+0.17 \pm 0.15 \pm 0.03$
$\phi K_0^*(1430)^0$		Breit-Wigner [7]					$4.6 \pm 0.7 \pm 0.6$	

TABLE II.　Summary of polarization results. The dominant fit correlation coefficients ($\mathcal{C}$) are presented for the $\phi K^*(892)^0$ mode where we show correlations of δ_0 with $\phi_\parallel/\phi_\perp$ and of $\Delta\delta_0$ with $\Delta\phi_\parallel/\Delta\phi_\perp$. For the $\phi K_2^*(1430)^0$ mode, the dominant values of $\mathcal{C}$ are 32% for $(\delta_0, \phi_\parallel)$ and 26% for $(\phi_\parallel, \phi_\perp)$.

	$B^0 \to \phi K_2^*(1430)^0$	$B^0 \to \phi K^*(892)^0$	$\mathcal{C}$
f_L	$0.853^{+0.061}_{-0.069} \pm 0.036$	$0.506 \pm 0.040 \pm 0.015$	$\left.\vphantom{\begin{matrix}a\\b\end{matrix}}\right\} -53\%$
$f_\perp$	$0.045^{+0.049}_{-0.040} \pm 0.013$	$0.227 \pm 0.038 \pm 0.013$	
$\phi_\parallel$	$2.90 \pm 0.39 \pm 0.06$	$2.31 \pm 0.14 \pm 0.08$	$\left.\vphantom{\begin{matrix}a\\b\end{matrix}}\right\} 61\%$
$\phi_\perp$	$5.72^{+0.55}_{-0.87} \pm 0.11$	$2.24 \pm 0.15 \pm 0.09$	
δ_0	$3.54^{+0.12}_{-0.14} \pm 0.06$	$2.78 \pm 0.17 \pm 0.09$	37%/27%
$\mathcal{A}_{CP}^0$	$\cdots$	$-0.03 \pm 0.08 \pm 0.02$	$\left.\vphantom{\begin{matrix}a\\b\end{matrix}}\right\} -51\%$
$\mathcal{A}_{CP}^\perp$	$\cdots$	$-0.03 \pm 0.16 \pm 0.05$	
$\Delta\phi_\parallel$	$\cdots$	$+0.24 \pm 0.14 \pm 0.08$	$\left.\vphantom{\begin{matrix}a\\b\end{matrix}}\right\} 61\%$
$\Delta\phi_\perp$	$\cdots$	$+0.19 \pm 0.15 \pm 0.08$	
$\Delta\delta_0$	$\cdots$	$+0.21 \pm 0.17 \pm 0.08$	37%/27%

whereas the vector-vector mode contains substantial A_{+1} amplitude from a presently unknown source either within or beyond the standard model [6].

*Also with Università di Perugia, Dipartimento di Fisica, Perugia, Italy
†Also with Università della Basilicata, Potenza, Italy
‡Also with IPPP, Physics Department, Durham University, Durham DH1 3LE, United Kingdom

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