Observation and Polarization Measurements of $B^{\pm} \to \varphi K_1^{\pm}$ and $B^{\pm} \to \varphi K_2^{*\pm}$

B. Aubert,[1] M. Bona,[1] Y. Karyotakis,[1] J. P. Lees,[1] V. Poireau,[1] E. Prencipe,[1] X. Prudent,[1] V. Tisserand,[1]
J. Garra Tico,[2] E. Grauges,[2] L. Lopez[ab],[3] A. Palano[ab],[3] M. Pappagallo[ab],[3] G. Eigen,[4] B. Stugu,[4] L. Sun,[4]
G. S. Abrams,[5] M. Battaglia,[5] D. N. Brown,[5] R. N. Cahn,[5] R. G. Jacobsen,[5] L. T. Kerth,[5] Yu. G. Kolomensky,[5]
G. Kukartsev,[5] G. Lynch,[5] I. L. Osipenkov,[5] M. T. Ronan,[5, *] K. Tackmann,[5] T. Tanabe,[5] C. M. Hawkes,[6]
N. Soni,[6] A. T. Watson,[6] H. Koch,[7] T. Schroeder,[7] D. Walker,[8] D. J. Asgeirsson,[9] B. G. Fulsom,[9]
C. Hearty,[9] T. S. Mattison,[9] J. A. McKenna,[9] M. Barrett,[10] A. Khan,[10] L. Teodorescu,[10] V. E. Blinov,[11]
A. D. Bukin,[11] A. R. Buzykaev,[11] V. P. Druzhinin,[11] V. B. Golubev,[11] A. P. Onuchin,[11] S. I. Serednyakov,[11]
Yu. I. Skovpen,[11] E. P. Solodov,[11] K. Yu. Todyshev,[11] M. Bondioli,[12] S. Curry,[12] I. Eschrich,[12] D. Kirkby,[12]
A. J. Lankford,[12] P. Lund,[12] M. Mandelkern,[12] E. C. Martin,[12] D. P. Stoker,[12] S. Abachi,[13] C. Buchanan,[13]
J. W. Gary,[14] F. Liu,[14] O. Long,[14] B. C. Shen,[14, *] G. M. Vitug,[14] Z. Yasin,[14] L. Zhang,[14] V. Sharma,[15]
C. Campagnari,[16] T. M. Hong,[16] D. Kovalskyi,[16] M. A. Mazur,[16] J. D. Richman,[16] T. W. Beck,[17] A. M. Eisner,[17]
C. J. Flacco,[17] C. A. Heusch,[17] J. Kroseberg,[17] W. S. Lockman,[17] T. Schalk,[17] B. A. Schumm,[17] A. Seiden,[17]
L. Wang,[17] M. G. Wilson,[17] L. O. Winstrom,[17] C. H. Cheng,[18] D. A. Doll,[18] B. Echenard,[18] F. Fang,[18]
D. G. Hitlin,[18] I. Narsky,[18] T. Piatenko,[18] F. C. Porter,[18] R. Andreassen,[19] G. Mancinelli,[19] B. T. Meadows,[19]
K. Mishra,[19] M. D. Sokoloff,[19] P. C. Bloom,[20] W. T. Ford,[20] A. Gaz,[20] J. F. Hirschauer,[20] A. Kreisel,[20]
M. Nagel,[20] U. Nauenberg,[20] J. G. Smith,[20] K. A. Ulmer,[20] S. R. Wagner,[20] R. Ayad,[21, †] A. Soffer,[21, ‡]
W. H. Toki,[21] R. J. Wilson,[21] D. D. Altenburg,[22] E. Feltresi,[22] A. Hauke,[22] H. Jasper,[22] M. Karbach,[22] J. Merkel,[22]
A. Petzold,[22] B. Spaan,[22] K. Wacker,[22] M. J. Kobel,[23] W. F. Mader,[23] R. Nogowski,[23] K. R. Schubert,[23]
R. Schwierz,[23] J. E. Sundermann,[23] A. Volk,[23] D. Bernard,[24] G. R. Bonneaud,[24] E. Latour,[24] Ch. Thiebaux,[24]
M. Verderi,[24] P. J. Clark,[25] W. Gradl,[25] S. Playfer,[25] J. E. Watson,[25] M. Andreotti[ab],[26] D. Bettoni[a],[26] C. Bozzi[a],[26]
R. Calabrese[ab],[26] A. Cecchi[ab],[26] G. Cibinetto[ab],[26] P. Franchini[ab],[26] E. Luppi[ab],[26] M. Negrini[ab],[26] A. Petrella[ab],[26]
L. Piemontese[a],[26] V. Santoro[ab],[26] R. Baldini-Ferroli,[27] A. Calcaterra,[27] R. de Sangro,[27] G. Finocchiaro,[27]
S. Pacetti,[27] P. Patteri,[27] I. M. Peruzzi,[27, §] M. Piccolo,[27] M. Rama,[27] A. Zallo,[27] A. Buzzo[a],[28] R. Contri[ab],[28]
M. Lo Vetere[ab],[28] M. M. Macri[a],[28] M. R. Monge[ab],[28] S. Passaggio[a],[28] C. Patrignani[ab],[28] E. Robutti[a],[28]
A. Santroni[ab],[28] S. Tosi[ab],[28] K. S. Chaisanguanthum,[29] M. Morii,[29] J. Marks,[30] S. Schenk,[30] U. Uwer,[30]
V. Klose,[31] H. M. Lacker,[31] D. J. Bard,[32] P. D. Dauncey,[32] J. A. Nash,[32] W. Panduro Vazquez,[32] M. Tibbetts,[32]
P. K. Behera,[33] X. Chai,[33] M. J. Charles,[33] U. Mallik,[33] J. Cochran,[34] H. B. Crawley,[34] L. Dong,[34] W. T. Meyer,[34]
S. Prell,[34] E. I. Rosenberg,[34] A. E. Rubin,[34] Y. Y. Gao,[35] A. V. Gritsan,[35] Z. J. Guo,[35] C. K. Lae,[35] A. G. Denig,[36]
M. Fritsch,[36] G. Schott,[36] N. Arnaud,[37] J. Béquilleux,[37] A. D'Orazio,[37] M. Davier,[37] J. Firmino da Costa,[37]
G. Grosdidier,[37] A. Höcker,[37] V. Lepeltier,[37] F. Le Diberder,[37] A. M. Lutz,[37] S. Pruvot,[37] P. Roudeau,[37]
M. H. Schune,[37] J. Serrano,[37] V. Sordini,[37, ¶] A. Stocchi,[37] G. Wormser,[37] D. J. Lange,[38] D. M. Wright,[38]
I. Bingham,[39] J. P. Burke,[39] C. A. Chavez,[39] J. R. Fry,[39] E. Gabathuler,[39] R. Gamet,[39] D. E. Hutchcroft,[39]
D. J. Payne,[39] C. Touramanis,[39] A. J. Bevan,[40] C. K. Clarke,[40] K. A. George,[40] F. Di Lodovico,[40] R. Sacco,[40]
M. Sigamani,[40] G. Cowan,[41] H. U. Flaecher,[41] D. A. Hopkins,[41] S. Paramesvaran,[41] F. Salvatore,[41] A. C. Wren,[41]
D. N. Brown,[42] C. L. Davis,[42] K. E. Alwyn,[43] D. S. Bailey,[43] R. J. Barlow,[43] R. J. Barlow,[43] Y. M. Chia,[43]
C. L. Edgar,[43] G. D. Lafferty,[43] T. J. West,[43] J. I. Yi,[43] J. Anderson,[44] C. Chen,[44] A. Jawahery,[44] D. A. Roberts,[44]
G. Simi,[44] J. M. Tuggle,[44] C. Dallapiccola,[45] X. Li,[45] E. Salvati,[45] S. Saremi,[45] R. Cowan,[46] D. Dujmic,[46]
P. H. Fisher,[46] K. Koeneke,[46] G. Sciolla,[46] M. Spitznagel,[46] F. Taylor,[46] R. K. Yamamoto,[46] M. Zhao,[46]
P. M. Patel,[47] S. H. Robertson,[47] A. Lazzaro[ab],[48] V. Lombardo[a],[48] F. Palombo[ab],[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] M. Simard,[50]
P. Taras,[50] F. B. Viaud,[50] H. Nicholson,[51] G. De Nardo[ab],[52] L. Lista[a],[52] D. Monorchio[ab],[52] G. Onorato[ab],[52]
C. Sciacca[ab],[52] G. Raven,[53] H. L. Snoek,[53] C. P. Jessop,[54] K. J. Knoepfel,[54] J. M. LoSecco,[54] W. F. Wang,[54]
G. Benelli,[55] L. A. Corwin,[55] K. Honscheid,[55] H. Kagan,[55] R. Kass,[55] J. P. Morris,[55] A. M. Rahimi,[55]
J. J. Regensburger,[55] S. J. Sekula,[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] R. Rahmat,[56] N. B. Sinev,[56] D. Strom,[56] J. Strube,[56] E. Torrence,[56] G. Castelli[ab],[57]
N. Gagliardi[ab],[57] M. Margoni[ab],[57] M. Morandin[a],[57] M. Posocco[a],[57] M. Rotondo[a],[57] F. Simonetto[ab],[57] R. Stroili[ab],[57]
C. Voci[ab],[57] P. del Amo Sanchez,[58] E. Ben-Haim,[58] H. Briand,[58] G. Calderini,[58] J. Chauveau,[58] P. David,[58]
L. Del Buono,[58] O. Hamon,[58] Ph. Leruste,[58] J. Ocariz,[58] A. Perez,[58] J. Prendki,[58] L. Gladney,[59] M. Biasini[ab],[60]
R. Covarelli[ab],[60] E. Manoni[ab],[60] C. Angelini[ab],[61] G. Batignani[ab],[61] S. Bettarini[ab],[61] M. Carpinelli[ab],[61, ††]
A. Cervelli[ab],[61] F. Forti[ab],[61] M. A. Giorgi[ab],[61] A. Lusiani[ac],[61] G. Marchiori[ab],[61] M. Morganti[ab],[61] N. Neri[ab],[61]
E. Paoloni[ab],[61] G. Rizzo[ab],[61] J. J. Walsh[a],[61] J. Biesiada,[62] D. Lopes Pegna,[62] C. Lu,[62] J. Olsen,[62] A. J. S. Smith,[62]
A. V. Telnov,[62] F. Anulli[a],[63] E. Baracchini[ab],[63] G. Cavoto[a],[63] D. del Re[ab],[63] E. Di Marco[ab],[63] R. Faccini[ab],[63]
F. Ferrarotto[a],[63] F. Ferroni[ab],[63] M. Gaspero[ab],[63] P. D. Jackson[a],[63] L. Li Gioi[a],[63] M. A. Mazzoni[a],[63] S. Morganti[a],[63]
G. Piredda[a],[63] F. Polci[ab],[63] F. Renga[ab],[63] C. Voena[a],[63] M. Ebert,[64] T. Hartmann,[64] H. Schröder,[64] R. Waldi,[64]
T. Adye,[65] B. Franek,[65] E. O. Olaiya,[65] W. Roethel,[65] F. F. Wilson,[65] S. Emery,[66] M. Escalier,[66] L. Esteve,[66]
A. Gaidot,[66] S. F. Ganzhur,[66] G. Hamel de Monchenault,[66] W. Kozanecki,[66] G. Vasseur,[66] Ch. Yèche,[66]
M. Zito,[66] X. R. Chen,[67] H. Liu,[67] W. Park,[67] M. V. Purohit,[67] R. M. White,[67] J. R. Wilson,[67] M. T. Allen,[68]
D. Aston,[68] R. Bartoldus,[68] P. Bechtle,[68] J. F. Benitez,[68] R. Cenci,[68] J. P. Coleman,[68] M. R. Convery,[68]
J. C. Dingfelder,[68] J. Dorfan,[68] G. P. Dubois-Felsmann,[68] W. Dunwoodie,[68] R. C. Field,[68] A. M. Gabareen,[68]
S. J. Gowdy,[68] M. T. Graham,[68] P. Grenier,[68] C. Hast,[68] W. R. Innes,[68] J. Kaminski,[68] M. H. Kelsey,[68] H. Kim,[68]
P. Kim,[68] M. L. Kocian,[68] D. W. G. S. Leith,[68] S. Li,[68] B. Lindquist,[68] S. Luitz,[68] V. Luth,[68] H. L. Lynch,[68]
D. B. MacFarlane,[68] H. Marsiske,[68] R. Messner,[68] D. R. Muller,[68] H. Neal,[68] S. Nelson,[68] C. P. O'Grady,[68] I. Ofte,[68]
A. Perazzo,[68] M. Perl,[68] B. N. Ratcliff,[68] A. Roodman,[68] A. A. Salnikov,[68] R. H. Schindler,[68] J. Schwiening,[68]
A. Snyder,[68] D. Su,[68] M. K. Sullivan,[68] K. Suzuki,[68] S. K. Swain,[68] J. M. Thompson,[68] J. Va'vra,[68] A. P. Wagner,[68]
M. Weaver,[68] C. A. West,[68] W. J. Wisniewski,[68] M. Wittgen,[68] D. H. Wright,[68] H. W. Wulsin,[68] A. K. Yarritu,[68]
K. Yi,[68] C. C. Young,[68] V. Ziegler,[68] P. R. Burchat,[69] A. J. Edwards,[69] S. A. Majewski,[69] T. S. Miyashita,[69]
B. A. Petersen,[69] L. Wilden,[69] S. Ahmed,[70] M. S. Alam,[70] J. A. Ernst,[70] B. Pan,[70] M. A. Saeed,[70] S. B. Zain,[70]
S. M. Spanier,[71] B. J. Wogsland,[71] R. Eckmann,[72] J. L. Ritchie,[72] A. M. Ruland,[72] C. J. Schilling,[72]
R. F. Schwitters,[72] B. W. Drummond,[73] J. M. Izen,[73] X. C. Lou,[73] F. Bianchi[ab],[74] D. Gamba[ab],[74] M. Pelliccioni[ab],[74]
M. Bomben[ab],[75] L. Bosisio[ab],[75] C. Cartaro[ab],[75] G. Della Ricca[ab],[75] L. Lanceri[ab],[75] L. Vitale[ab],[75] V. Azzolini,[76]
N. Lopez-March,[76] F. Martinez-Vidal,[76] D. A. Milanes,[76] A. Oyanguren,[76] J. Albert,[77] Sw. Banerjee,[77]
B. Bhuyan,[77] H. H. F. Choi,[77] K. Hamano,[77] R. Kowalewski,[77] M. J. Lewczuk,[77] I. M. Nugent,[77] J. M. Roney,[77]
R. J. Sobie,[77] T. J. Gershon,[78] P. F. Harrison,[78] J. Ilic,[78] T. E. Latham,[78] G. B. Mohanty,[78] H. R. Band,[79]
X. Chen,[79] S. Dasu,[79] K. T. Flood,[79] Y. Pan,[79] M. Pierini,[79] R. Prepost,[79] C. O. Vuosalo,[79] and S. L. Wu[79]

(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]*INFN Sezione di Bari[a]; Dipartimento di Fisica, Università di Bari[b], I-70126 Bari, Italy*
[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 Riverside, Riverside, California 92521, USA*
[15]*University of California at San Diego, La Jolla, California 92093, USA*
[16]*University of California at Santa Barbara, Santa Barbara, California 93106, USA*
[17]*University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA*
[18]*California Institute of Technology, Pasadena, California 91125, USA*
[19]*University of Cincinnati, Cincinnati, Ohio 45221, USA*
[20]*University of Colorado, Boulder, Colorado 80309, USA*
[21]*Colorado State University, Fort Collins, Colorado 80523, USA*
[22]*Technische Universität Dortmund, Fakultät Physik, D-44221 Dortmund, Germany*
[23]*Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany*
[24]*Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, F-91128 Palaiseau, France*
[25]*University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom*

[26]INFN Sezione di Ferrara[a]; Dipartimento di Fisica, Università di Ferrara[b], I-44100 Ferrara, Italy
[27]INFN Laboratori Nazionali di Frascati, I-00044 Frascati, Italy
[28]INFN Sezione di Genova[a]; Dipartimento di Fisica, Università di Genova[b], I-16146 Genova, Italy
[29]Harvard University, Cambridge, Massachusetts 02138, USA
[30]Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany
[31]Humboldt-Universität zu Berlin, Institut für Physik, Newtonstr. 15, D-12489 Berlin, 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, 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]INFN Sezione di Milano[a]; Dipartimento di Fisica, Università di Milano[b], 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]INFN Sezione di Napoli[a]; Dipartimento di Scienze Fisiche,
Università di Napoli Federico II[b], 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]INFN Sezione di Padova[a]; Dipartimento di Fisica, Università di Padova[b], 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]INFN Sezione di Perugia[a]; Dipartimento di Fisica, Università di Perugia[b], I-06100 Perugia, Italy
[61]INFN Sezione di Pisa[a]; Dipartimento di Fisica,
Università di Pisa[b]; Scuola Normale Superiore di Pisa[c], I-56127 Pisa, Italy
[62]Princeton University, Princeton, New Jersey 08544, USA
[63]INFN Sezione di Roma[a]; Dipartimento di Fisica,
Università di Roma La Sapienza[b], I-00185 Roma, Italy
[64]Universität Rostock, D-18051 Rostock, Germany
[65]Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom
[66]DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France
[67]University of South Carolina, Columbia, South Carolina 29208, USA
[68]Stanford Linear Accelerator Center, Stanford, California 94309, USA
[69]Stanford University, Stanford, California 94305-4060, USA
[70]State University of New York, Albany, New York 12222, USA
[71]University of Tennessee, Knoxville, Tennessee 37996, USA
[72]University of Texas at Austin, Austin, Texas 78712, USA
[73]University of Texas at Dallas, Richardson, Texas 75083, USA
[74]INFN Sezione di Torino[a]; Dipartimento di Fisica Sperimentale, Università di Torino[b], I-10125 Torino, Italy
[75]INFN Sezione di Trieste[a]; Dipartimento di Fisica, Università di Trieste[b], I-34127 Trieste, Italy
[76]IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain
[77]University of Victoria, Victoria, British Columbia, Canada V8W 3P6
[78]Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom
[79]University of Wisconsin, Madison, Wisconsin 53706, USA
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With the full BABAR data sample of 465×10^6 $B\overline{B}$ pairs, we observe the decays $B^{\pm} \to \varphi K_1(1270)^{\pm}$ and $B^{\pm} \to \varphi K_2^*(1430)^{\pm}$. We measure the branching fractions $(6.1 \pm 1.6 \pm 1.1) \times 10^{-6}$ and $(8.4 \pm$

$1.8 \pm 1.0) \times 10^{-6}$ and the fractions of longitudinal polarization $0.46^{+0.12+0.06}_{-0.13-0.07}$ and $0.80^{+0.09}_{-0.10} \pm 0.03$, respectively. We also report on the $B^{\pm} \to \varphi K_0^*(1430)^{\pm}$ decay branching fraction of $(7.0 \pm 1.3 \pm 0.9) \times 10^{-6}$ and several parameters sensitive to CP violation and interference in the above three decays. Upper limits are placed on the $B^{\pm}$ decay rates to final states with φ and $K_1(1400)^{\pm}$, $K^*(1410)^{\pm}$, $K_2(1770)^{\pm}$, or $K_2(1820)^{\pm}$. Understanding the observed polarization pattern requires amplitude contributions from an uncertain source.

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Measurements of polarization in rare vector-vector B meson decay, such as $B \to \varphi K^*$ [1, 2], have revealed an unexpectedly large fraction of transverse polarization and suggested contributions to the decay amplitude which were previously neglected. Decays to other excited spin-J kaons $K_J^{(*)}$ can also take place. The differential width for a $B \to \varphi K_J^{(*)}$ decay has three complex amplitudes $A_{J\lambda}$, which describe the three helicity states $\lambda = 0, \pm 1$, except when $J = 0$. The expected hierarchy of the $A_{J\lambda}$ amplitudes $|A_{J0}|^2 \gg |A_{J+}|^2 \gg |A_{J-}|^2$ is sensitive to the $(V - A)$ structure of the weak interactions with the left-handed fermion couplings [3–5], and therefore is sensitive to physics beyond the standard model. For example, tensor or scalar interactions would violate $|A_{J0}|^2 \gg |A_{J+}|^2$ and the right-handed fermion couplings would violate $|A_{J+}|^2 \gg |A_{J-}|^2$ [3]. Strong interaction effects could change these predictions as well, but were originally expected to be small [3].

However, all previous studies have been limited to the two-body $K_J^* \to K\pi$ decays, thus considering only the spin-parity K_J^* states with $P = (-1)^J$. In this paper we report the measurement with the three-body final states $K_J^{(*)} \to K\pi\pi$ which include $P = (-1)^{J+1}$ mesons such as K_1 and K_2. We complement these measurements with the two-body $K_J^{(*)}$ final states in the $B^{\pm}$ decays and report polarization in the $\varphi K_1(1270)^{\pm}$ and $\varphi K_2^*(1430)^{\pm}$ final states which have not been seen before. We also search for other final states with φ and $K_0^*(1430)^{\pm}$, $K_1(1400)^{\pm}$, $K^*(1410)^{\pm}$, $K_2(1770)^{\pm}$, or $K_2(1820)^{\pm}$.

We use data collected with the *BABAR* detector [6] at the PEP-II e^+e^- collider. A sample of $(465 \pm 5) \times 10^6$ $\Upsilon(4S) \to B\overline{B}$ events was recorded at the the e^+e^- center-of-mass energy $\sqrt{s} = 10.58\,\text{GeV}$. Momenta of charged particles 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. Identification of charged particles is provided by measurements of the energy loss in the tracking devices and by a ring-imaging Cherenkov detector. Photons are detected by a CsI(Tl) electromagnetic calorimeter.

We search for $B^{\pm} \to \varphi K_J^{(*)\pm}$ decays using three final states of the $K_J^{(*)\pm}$ decay: $K_S^0\pi^{\pm}$, $K^{\pm}\pi^0$, and $K^{\pm}\pi^+\pi^-$, where $K_S^0 \to \pi^+\pi^-$ and $\pi^0 \to \gamma\gamma$. We define the two helicity angles θ_i as the angle between the direction of the K or K^+ meson from $K^* \to K\pi$ (θ_1) or $\varphi \to K^+K^-$

(θ_2) and the direction opposite to the B in the K^* or φ rest frame. The normal to the three-body decay plane for $K_J^{(*)} \to K\pi\pi$ is chosen as the analyzer of the $K_J^{(*)}$ polarization instead of the direction of K from K_J^* in the two-body decays. We define $\mathcal{H}_i = \cos\theta_i$.

We identify B meson candidates using two kinematic variables: $m_{\text{ES}} = (s/4 - \mathbf{p}_B^2)^{1/2}$ and $\Delta E = \sqrt{s}/2 - E_B$, where $(E_B, \mathbf{p}_B)$ is the four-momentum of the B candidate in the e^+e^- center-of-mass frame. We require $m_{\text{ES}} > 5.25$ GeV and $|\Delta E| < 0.1$ GeV (or 0.08 GeV for $K_J^{(*)\pm} \to K^{\pm}\pi^+\pi^-$) GeV. We also require the invariant masses to satisfy $1.1 < m_{K\pi} < 1.6$ GeV, $1.1 < m_{K\pi\pi} < 2.1$ GeV, and $0.99 < m_{K^+K^-} < 1.05$ GeV. To reject the dominant $e^+e^- \to$ light quark-antiquark background, we use the angle θ_T between the thrust axis of the B-candidate decay products and that of the rest of the event requiring $|\cos\theta_T| < 0.8$, and a Fisher discriminant $\mathcal{F}$ which combines event-shape parameters [7].

To reduce combinatorial background in the mode $K_J^{*\pm} \to K^{\pm}\pi^0$, we require $\mathcal{H}_1 < 0.6$. When more than one candidate is reconstructed (7.6% of events with $K_S^0\pi^{\pm}$, 2.9% with $K^{\pm}\pi^0$, and 14.6% with $K^{\pm}\pi^+\pi^-$), we select the one whose χ^2 of the charged-track vertex fit combined with χ^2 of the invariant mass consistency of the K_S^0 or π^0 candidate, is the lowest. We define the b-quark flavor sign Q to be opposite to the charge of the B meson candidate.

We use an unbinned extended maximum-likelihood fit [1] to extract the event yields n_j and the probability density function (PDF) parameters, denoted by $\boldsymbol{\zeta}$ and $\boldsymbol{\xi}$, to be described below. The index j represents the event categories, which include continuum background and several B-decay modes. In the $B^{\pm} \to \varphi K_J^{*\pm} \to (K^+K^-)(K\pi)$ topology, the following event categories are considered: $\varphi K_2^*(1430)^{\pm}$, $\varphi(K\pi)_0^{*\pm}$, and $f_0(K\pi)_0^{*\pm}$, where the $J^P = 0^+$ $(K\pi)_0^{*\pm}$ contribution includes both a nonresonant component and the $K_0^*(1430)^{\pm}$ resonance [8]. In the $B^{\pm} \to \varphi K_J^{(*)\pm} \to (K^+K^-)(K\pi\pi)$ topology, we consider $\varphi K_1(1270)^{\pm}$, $\varphi K_1(1400)^{\pm}$, $\varphi K_2^*(1430)^{\pm}$, $\varphi K^*(1410)^{\pm}$, $\varphi K_2(1820)^{\pm}$, a nonresonant $\varphi K^{\pm}\pi^+\pi^-$, and $f_0 K_1(1400)^{\pm}$ contributions. In the latter topology, the mode $\varphi K_2(1770)^{\pm}$ is also considered in place of $\varphi K_2(1820)^{\pm}$. In all cases, the modes with f_0 model can account for a possible broad non-φ (K^+K^-) contributions under the φ.

The extended likelihood is $\mathcal{L} = \exp(-\sum n_j) \prod \mathcal{L}_i$. The likelihood $\mathcal{L}_i$ for candidate i is defined as $\mathcal{L}_i =$

$\sum_{j,k} n_j^k \mathcal{P}_j^k(\mathbf{x}_i; \boldsymbol{\zeta}, \boldsymbol{\xi})$, where $\mathcal{P}_j^k$ is the PDF for variables $\mathbf{x_i} = \{\mathcal{H}_1, \mathcal{H}_2, m_{K\pi(\pi)}, m_{K^+K^-}, \Delta E, m_{ES}, \mathcal{F}, Q\}$. The flavor index k corresponds to the value of Q, that is $\mathcal{P}_j^k \equiv \mathcal{P}_j \times \delta_{kQ}$. The $\boldsymbol{\zeta}$ are the polarization parameters, only relevant for the signal PDF. The $\boldsymbol{\xi}$ parameters describe the background or the remaining signal PDFs, which are left free to vary in the fit for the combinatorial background and are fixed to the values extracted from Monte Carlo (MC) simulation [9] and calibration $B \to \overline{D}\pi$ decays in other cases.

The signal PDF for a given candidate i is a joint PDF for the helicity angles and resonance mass, and the product of the PDFs for each of the remaining variables. The helicity part of the signal PDF is the ideal angular distribution from Ref. [10], multiplied by an empirical acceptance function $\mathcal{G}(\mathcal{H}_1, \mathcal{H}_2)$. In the $B \to \varphi K_1$ or φK_2 parameterization, the additional kinematic parameters for the decays $K_J^\pm \to K^\pm\pi^+\pi^-$ (such as r_1, r_2, and r_{02} in Ref. [10]) are modeled using the sequential two-body decay chains [5]. A relativistic spin-J Breit–Wigner amplitude parameterization is used for the resonance masses [5, 11], and the $J^P = 0^+$ $(K\pi)_0^{*\pm}$ $m_{K\pi}$ amplitude is parameterized with the LASS function [8]. The nonresonant $\varphi K^\pm\pi^+\pi^-$ contribution is modeled through sequential $K^*(892)\pi \to K\pi\pi$ decay, while the decay $K\rho \to K\pi\pi$ is considered in the systematic uncertainty studies. We use a sum of Gaussian functions for the parameterization of ΔE, m_{ES}, and $\mathcal{F}$.

The interference between the $J = 2$ and 0 $(K\pi)^\pm$ contributions is modeled with the term $2\mathcal{Re}(A_{20}A_{00}^*)$, with the three-dimensional angular and $m_{K\pi}$ parameterization. We allow an unconstrained flavor-dependent overall shift $(\delta_0 + \Delta\delta_0 \times Q)$ between the LASS amplitude phase and the tensor resonance amplitude phase. The polarization parameters $\boldsymbol{\zeta}$ include the fractions of longitudinal polarization $f_L = |A_{J0}|^2/\Sigma|A_{J\lambda}|^2$ in several channels, δ_0, and $\Delta\delta_0$. Similar interference between the $K_1(1270)^\pm$ and $K_1(1400)^\pm$ contributions is allowed in the study of systematic uncertainties but is not included in the nominal fit due to observed dominance of only one mode and therefore unconstrained phase of the interference.

Since the $K_2^*(1430)^\pm$ meson contributes to all three $K^0\pi^\pm$, $K^\pm\pi^0$, and $K^\pm\pi^+\pi^-$ final states and $(K\pi)_0^{*\pm}$ contributes to two $K\pi$ final states in this analysis, we consider the total $\mathcal{L}$ as a product of three likelihoods constructed for each of the three channels. The corresponding yields in different channels are related by the relative efficiency. We fit the yields in each charge category k independently and report them in the form of the total yield $n_j = n_j^+ + n_j^-$ and direct-CP asymmetry $\mathcal{A}_{CP} = (n_j^+ - n_j^-)/n_j$.

The combinatorial background PDF is the product of the PDFs for independent variables and is found to describe well both the dominant quark-antiquark background and the background from random combinations of B tracks. We use polynomials for the PDFs, except
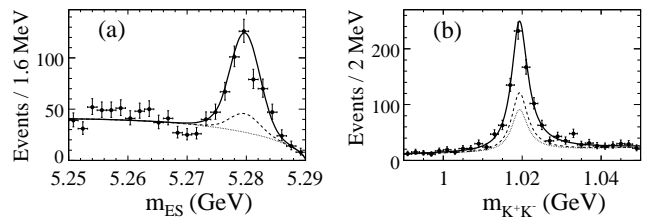

FIG. 1: Projections onto the variables m_{ES} (a), and $m_{K\overline{K}}$ (b) for the signal $B^+ \to \varphi(K\pi)$ and $B^+ \to \varphi(K\pi\pi)$ candidates. Data distributions are shown with a requirement on the signal-to-background probability ratio calculated with the plotted variable excluded. The solid (dotted) lines show the signal-plus-background (combinatorial background) PDF projections, while the dashed lines show the full PDF projections excluding the signal.

for m_{ES} and $\mathcal{F}$ distributions which are parameterized by an empirical phase-space function and by Gaussian functions, respectively. Resonance production occurs in the background and is taken into account in the PDF.

We observe nonzero $B^\pm \to \varphi K_1(1270)^\pm$ and $B^\pm \to \varphi K_2^*(1430)^\pm$ yields with significance (excluding systematic uncertainties in parentheses) of $5.0(5.3)\sigma$ and $5.5(6.0)\sigma$, respectively. The combined $\varphi K_1(1270)^\pm$ and $\varphi K_1(1400)^\pm$ significance is $5.7(6.4)\sigma$. 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 $\mathcal{L}$. We have tested this procedure with the generated MC samples and account for a small observed deviation from the one-dimensional χ^2 statistical treatment.

In Table I, results of the fit are presented, where the combined results are obtained from the simultaneous fit to the three decay subchannels. In the branching fraction calculations we assume $K_2 \to K_2^*(1430)\pi$ and $\mathcal{B}(K^*(1410) \to K^*\pi) = 0.934 \pm 0.013$ [5]. The signal is illustrated in the projection plots in Figs. 1 and 2, where in the latter we enhance either the $\varphi K_1(1270)^\pm$ signal (left) or the $\varphi K_2^*(1430)^\pm$ signal (right). The nonresonant K^+K^- contribution under the φ is accounted for with the $B^0 \to f_0 K_1$ category and its yield 7 ± 16 is consistent with zero. Similarly, the nonresonant category $\varphi K\pi\pi$ yield is 148 ± 54 with statistical errors only.

We vary those parameters in $\boldsymbol{\xi}$ not used to model combinatorial background within their uncertainties and derive the associated systematic errors. Interference between the $K_1(1270)^\pm$ and $K_1(1400)^\pm$ is one of the dominant systematic uncertainties on both yields and is modeled with simulated samples. We take the flavor-dependent reconstruction efficiency into account in the study of asymmetries. The biases from the finite resolution of the angle measurement, the dilution due to the presence of false combinations, and other imperfections in the signal PDF model are estimated with MC simulation. Additional systematic uncertainty originates from possible B background, where we estimate from MC simulation that only a few events can fall in the signal region.

TABLE I: Results: the reconstruction efficiency $\varepsilon_{\text{reco}}$; the total efficiency ε, including the daughter branching fractions [5]; the number of signal events n_{sig}; significance $\mathcal{S}$; fraction of longitudinal polarization f_L; the branching fraction $\mathcal{B}$; and the flavor asymmetry $\mathcal{A}_{CP}$. The branching fraction $\mathcal{B}(B^\pm \to \varphi(K\pi)_0^{*\pm})$ refers to the coherent sum $|A_{\text{res}} + A_{\text{non-res}}|^2$ of resonant and nonresonant $J^P = 0^+$ $K\pi$ components [8] and is quoted for $m_{K\pi} < 1.6$ GeV, while the $\mathcal{B}(B^\pm \to \varphi K_0^*(1430)^\pm)$ is derived from it by integrating separately the Breit-Wigner formula of the resonant $|A_{\text{res}}|^2$ $K\pi$ component [8] without $m_{K\pi}$ restriction. When several subchannels contribute, yield and efficiency are quoted for each subchannel. The 90% confidence level upper limit on $\mathcal{B}$ is quoted with the central values and errors in parentheses. The insert shows two interference parameters δ_0 and $\Delta\delta_0$ for $\varphi K_2^*(1430)^\pm$ and $\varphi(K\pi)_0^{*\pm}$. The $\varphi K_2(1770)^\pm$ yield is not considered in the nominal fit and the value indicated with † is obtained with these $\varphi K_2(1820)^\pm$ yield constrained to zero. The systematic errors are quoted last.

Mode	$\varepsilon_{\text{reco}}$ (%)	ε (%)	n_{sig} (events)	$\mathcal{S}$ (σ)	f_L	$\mathcal{B}$ (10^{-6})	$\mathcal{A}_{CP}$
$\varphi K_1(1270)^\pm$	25.4 ± 1.4	4.07 ± 0.51	$116 \pm 26\,^{+15}_{-14}$	5.0	$0.46^{+0.12}_{-0.13}\,^{+0.06}_{-0.07}$	$6.1 \pm 1.6 \pm 1.1$	$+0.15 \pm 0.19 \pm 0.05$
$\varphi K_1(1400)^\pm$	24.6 ± 1.3	5.19 ± 0.44	$7 \pm 39 \pm 18$	0.2		$< 3.2\ (0.3 \pm 1.6 \pm 0.7)$	
$\varphi K_2^*(1430)^\pm$		3.34 ± 0.14	$130 \pm 27 \pm 14$	5.5	$0.80^{+0.09}_{-0.10} \pm 0.03$	$8.4 \pm 1.8 \pm 1.0$	$-0.23 \pm 0.19 \pm 0.06$
$\quad \to K_S^0 \pi^\pm$	11.9 ± 0.6	0.64 ± 0.04	$27 \pm 6 \pm 3$				
$\quad \to K^\pm \pi^0$	12.2 ± 0.7	1.00 ± 0.06	$39 \pm 8 \pm 4$		$\boxed{\delta_0 = 3.59 \pm 0.19 \pm 0.12 \qquad \Delta\delta_0 = -0.05 \pm 0.19 \pm 0.06}$		
$\quad \to K^\pm \pi^+ \pi^-$	24.7 ± 1.3	1.68 ± 0.12	$64 \pm 14 \pm 7$				
$\varphi(K\pi)_0^{*\pm}$		3.33 ± 0.13	$128 \pm 21 \pm 12$	8.2		$8.3 \pm 1.4 \pm 0.8$	$+0.04 \pm 0.15 \pm 0.04$
$\quad \to K_S^0 \pi^\pm$	10.9 ± 0.6	1.24 ± 0.07	$48 \pm 8 \pm 4$				
$\quad \to K^\pm \pi^0$	12.8 ± 0.7	2.09 ± 0.12	$80 \pm 13 \pm 8$				
$\varphi K_0^*(1430)^\pm$						$7.0 \pm 1.3 \pm 0.9$	
$\varphi K^*(1410)^\pm$	28.0 ± 2.2	5.71 ± 0.44	$64 \pm 31\,^{+20}_{-31}$	< 2		$< 4.3\ (2.4 \pm 1.2\,^{+0.8}_{-1.2})$	
$\varphi K_2(1770)^\pm$	20.8 ± 1.4	2.27 ± 0.16	$(90 \pm 32\,^{+39}_{-46})^\dagger$	< 2		< 15.0	
$\varphi K_2(1820)^\pm$	21.6 ± 1.5	2.35 ± 0.18	$122 \pm 40\,^{+26}_{-83}$	< 2		< 16.3	

The $\varphi K_2(1770)^\pm$ yield is not considered in the nominal fit due to large correlation with $\varphi K_2(1820)^\pm$. But we substitute the $K_2(1820)$ resonance for the $K_2(1770)$ resonance, and find consistent results. The difference is accounted as a systematics uncertainty, while the yield of decay $B^\pm \to \varphi K_2(1770)^\pm$ is used to obtain its branching fraction. We quote only upper limits on the two branching fractions as their correlation is not accounted for in the central values. For the φK_2 and $\varphi K^*(1410)$ decays, we vary the longitudinal polarization fraction between 0.5 and 0.93, and constrain it to 0.8 in the nominal fit. Polarization variations are included in the branching fraction calculations. We vary the kinematic parameter describing $K_J^\pm \to K^\pm \pi^+ \pi^-$ decay (r_{02} in Ref. [10]) for various partial waves of the quasi-two-body K_2 decay channels and take the largest variations as the systematic uncertainties. The systematic uncertainties in efficiencies are dominated by those in particle identification, track finding, and K_S^0 and π^0 selection. Other systematic effects arise from event-selection criteria, φ and $K_J^{(*)}$ branching fractions, and number of B mesons.

In summary, we have performed an amplitude analysis and searched for CP-violation with the $B^\pm \to \varphi K_J^{(*)\pm}$ decays which include significant $K_1(1270)$ and $K_2^*(1430)$ contributions. Our results are summarized in Table I.

The polarization measurement in the vector–tensor $B^\pm$ decay is consistent with our earlier measurement in the $B^0 \to \varphi K_2^*(1430)^0$ decay [1] and with the naive expectation of the longitudinal polarization dominance. However, our first measurement of polarization in a vector–axial-vector B meson decay indicates a large fraction of transverse amplitude, similar to polarization observed in the vector–vector final state $B \to \varphi K^*(892)$ [1, 2]. Both measurements indicate substantial A_{1+1} (or still possible A_{1-1} for vector–axial-vector decay) amplitude from an uncertain source. Among potential sources are penguin annihilation, electroweak penguin, QCD rescattering, or physics beyond the standard model [3].
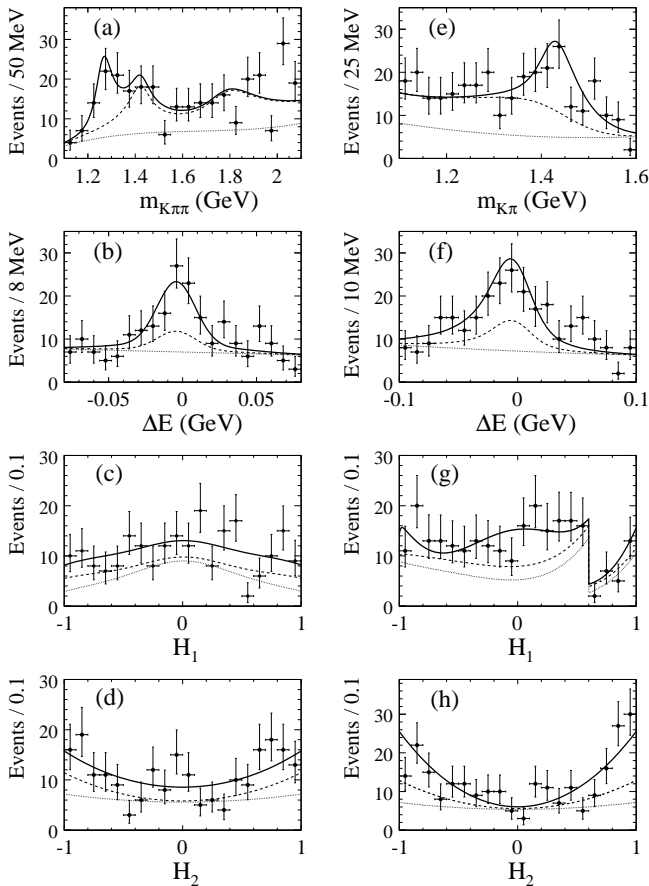
FIG. 2: Left column: projections onto the variables $m_{K\pi\pi}$ (a), ΔE (b), $\mathcal{H}_1$ (c), and $\mathcal{H}_2$ (d) for the signal $\varphi K_1(1270)^{\pm}$ candidate. Right column: projections onto the variables $m_{K\pi}$ (e), ΔE (f), $\mathcal{H}_1$ (g), and $\mathcal{H}_2$ (h) for the signal $\varphi K_2^*(1430)^{\pm}$ and $\varphi(K\pi)_0^{*\pm}$ candidates combined. The step in (g) is due to selection requirement $\mathcal{H}_1 < 0.6$ in the channel with π^0. Data distributions are shown with a requirement on the signal-to-background probability ratio calculated with the plotted variable excluded. The solid (dotted) lines show the signal-plus-background (combinatorial background) PDF projections, while the dashed lines show the full PDF projections excluding $\varphi K_1^{\pm}$ (left) or $\varphi K_2^*(1430)^{\pm}$ (right).

* Deceased
† Now at Temple University, Philadelphia, Pennsylvania 19122, USA
‡ Now at Tel Aviv University, Tel Aviv, 69978, Israel
§ Also with Università di Perugia, Dipartimento di Fisica, Perugia, Italy
¶ Also with Università di Roma La Sapienza, I-00185 Roma, Italy
** Now at University of South Alabama, Mobile, Alabama 36688, USA
†† Also with Università di Sassari, Sassari, Italy

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