Branching Fractions and $CP$ Asymmetries in $B^0 \to K^+K^-K^0_s$ and $B^+ \to K^+K^0_sK^0_s$

B. Aubert,1 R. Barate,1 D. Boutigny,1 F. Coudere,1 J.-M. Gaillard,1 A. Hicheur,1 Y. Karyotakis,1 J. P. Lees,1 V. Tisserand,1 A. Zghiche,1 A. Palano,2 A. Pomplii,2 J. C. Chen,3 N. D. Qi,3 G. Rong,3 P. Wang,3 Y. S. Zhu,3 G. Eigen,4 I. Olte,5 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 C. T. Day,5 M. S. Gill,5 A. V. Gritsan,5 Y. Gromysan,5 R. G. Jacobsen,5 R. W. Kadel,5 J. Kadyk,5 L. T. Kerth,5 Yu. G. Kolomensky,5 G. Kukartsev,5 G. Lynch,5 L. M. Mir,5 P. J. Oddone,5 T. J. Orimoto,5 M. Pripstein,5 N. A. Roe,5 M. T. Roman,5 V. G. Shelkov,5 W. A. Wenzel,5 M. Barrett,6 K. E. Ford,6 T. J. Harrison,6 A. J. Hart,6 C. M. Hawkes,6 S. E. Morgan,6 A. T. Watson,6 M. Fritsch,7 K. Goetz,7 T. Held,7 H. Koch,7 B. Lewandowski,7 M. Pelazuea,7 M. Steinke,7 J. T. Boyd,8 N. Chevalier,8 W. N. Cutttingham,8 M. P. Kelly,9 T. E. Latham,8 F. F. Wilson,8 T. Cuhadar-Donszelmann,9 C. Hearty,9 N. S. Knecht,9 T. S. Mattison,9 J. A. McKenna,9 D. Thiessen,9 A. Khan,10 P. Kyberd,10 L. Teodorescu,10 V. E. Blinov,11 V. P. Druzhinin,11 V. B. Golutiev,11 V. N. Ivanchenko,11 E. A. Kravchenko,11 A. P. Omchinnikov,12 S. I. Serednyakova,11 Yu. I. Skoppen,11 E. P. Solodov,11 A. N. Yushkov,11 D. Best,12 M. Bruimens,12 M. Chao,12 I. Eschrich,12 D. Kirbky,12 A. J. Lankford,12 M. Mandelkorn,12 R. K. Mommsen,12 W. Roethel,12 D. P. Stoker,12 C. Buchanan,13 B. L. Hartfiel,13 S. D. Foulkes,14 J. W. Gary,14 B. C. Shen,14 K. Wang,14 D. del Re,15 H. K. Hadavand,15 E. J. Hill,15 D. B. MacFarlane,15 H. P. Paar,15 Sh. Rahatlou,15 V. Sharma,15 J. S. Berryhill,16 C. Campagnari,16 B. Dahnnes,16 S. L. Levy,16 O. Long,16 A. Lu,16 M. A. Mazur,16 J. D. Richman,16 W. Verkerke,16 T. W. Beck,17 A. M. Eisner,17 C. A. Heusch,17 W. S. Lockman,17 T. Schalk,17 R. E. Schmitz,17 B. A. Schumm,17 A. Seiden,17 P. Spradlin,17 D. C. Williams,17 M. G. Wilson,17 J. Albert,18 E. Chen,18 G. P. Dubois-Felsmann,18 A. Divodetski,18 D. G. Hitlin,18 I. Narshy,18 T. Petenke,18 F. C. Porter,18 A. Ryd,18 A. Samuel,18 S. Yang,18 S. Jayatilleke,19 G. Mancinelli,19 B. T. Meadows,19 M. D. Sokoloff,19 T. Abe,20 F. Blanc,20 P. Bloom,20 S. Chen,20 W. T. Ford,20 U. Nauenberg,20 A. Olias,20 P. Rankin,20 J. G. Smith,20 J. Zhang,20 L. Zhang,20 A. Chen,21 J. L. Harton,21 A. Soffer,21 W. H. Toki,21 R. J. Wilson,21 Q. L. Zeng,21 D. Altenburg,22 T. Brandt,22 J. Brose,22 M. Dickopp,22 E. Feltresi,22 A. Hauke,22 H. M. Lackner,22 R. Müller-Pfeifferkorn,22 R. Nogowski,22 S. Otto,22 A. Petzold,22 J. Schubert,22 K. R. Schubert,22 R. Schierz,22 B. Spaan,22 J. E. Sundermann,22 D. Bernard,23 G. R. Bonneaud,23 F. Brochard,23 P. Grenier,23 S. Schrenk,23 C. Thiébaux,23 G. Vasileliadis,23 M. Verderi,23 D. J. Bard,24 P. J. Clark,24 D. Lavin,24 F. Mulheim,24 S. Playfer,24 Y. Xie,24 M. Andreotti,25 V. Azzolini,25 D. Bettoni,25 C. Bozzi,25 R. Calabrese,25 G. Cibinetto,25 E. Luppi,25 M. Negrini,25 L. Piemontese,25 A. Sarti,25 E. Tredwell,26 R. Baldini-Ferroli,27 A. Cacotta,27 R. de Sangro,27 G. Finocchiaro,27 P. Patteri,27 M. Piccolo,27 A. Zallo,27 A. Buzzo,28 R. Capra,28 R. Contri,28 G. Crosetti,28 M. Lo Vetere,28 M. Macri,28 M. R. Monge,28 S. Passaggio,28 C. Patrignani,28 E. Robutti,28 A. Santroni,28 S. Tosi,28 S. Bailey,29 G. Brandenburg,29 M. Morii,29 E. Won,29 R. S. Dubitzky,30 U. Langenegger,30 W. Bhimji,31 D. A. Bowerman,31 P. D. Dauncey,31 U. Egede,31 J. R. Gaillard,31 G. W. Morton,31 J. A. Nash,31 G. P. Taylor,31 J. M. Charles,32 G. J. Grenier,32 U. Mallik,32 J. Cochran,33 H. B. Crawley,33 J. Lamsa,33 W. T. Meyer,33 S. Prell,33 E. I. Rosenberg,33 J. Y. Yi,34 M. Davier,34 G. Grosdidier,34 A. Höcker,34 S. Laplace,34 F. Le Diberder,34 V. Lepeltier,34 A. M. Lutz,34 T. C. Petersen,34 S. Ptaszczyński,34 M. H. Schune,34 L. Tantot,34 G. Wormser,34 C. H. Cheng,35 D. J. Lange,35 M. C. Simani,35 D. M. Wright,35 A. J. Bevan,36 C. A. Chavez,36 J. P. Coleman,36 I. J. Forster,36 J. R. Fry,36 E. Gabathuler,36 R. Gamet,36 R. J. Parry,36 D. J. Payne,36 R. J. Sloane,36 C. Touramanis,36 J. J. Back,37 C. M. Cormick,37 P. F. Harrison,37 F. Di Lodovico,37 G. B. Molyant,37 C. L. Brown,38 G. Cowan,38 R. L. Flack,38 H. U. Flaecher,38 M. G. Green,38 P. S. Jackson,38 T. R. McMahone,38 S. Ricciardi,38 F. Salvatiero,38 M. A. Winter,38 D. Brown,39 C. L. Davis,39 J. Allison,40 N. R. Barlow,40 R. J. Barlow,40 P. A. Hart,40 M. C. Hodgkinson,40 G. D. Lafferty,40 A. J. Lyon,40 J. C. Williams,40 A. Farbin,41 W. D. Hulsbergen,41 A. Jawahery,41 D. Kovalskyi,41 C. K. Lai,41 V. Lillard,41 A. R. Roberts,41 G. Blaylock,42 C. DallaPiccola,42 K. T. Flood,42 S. S. Hertzbach,42 R. Koller,42 V. B. Koptchev,42 T. B. Moore,42 S. Sareni,42 H. Stangaell,42 S. Willocq,42 R. Cowan,43 G. Sciolla,43 F. Taylor,43 R. K. Yamamoto,43 D. J. J. Mangeol,44 P. M. Patet,44 S. H. Robertson,44 A. Lazzaro,45 F. Palombo,45 J. M. Bauer,46 L. Cremaldi,46 V. Eschenburg,46 R. Godang,46 R. Kroeger,46 J. Reidy,46 D. A. Sanders,46 D. J. Summers,46 H. W. Zhao,46 S. Brunet,47 D. Côté,47 P. Taras,47 H. Nicholson,48 N. Cavallo,49 F. Fabozzi,49
University of Cincinnati, Cincinnati, OH 45221, USA
University of Colorado, Boulder, CO 80309, USA
Colorado State University, Fort Collins, CO 80523, USA
Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany
Ecole Polytechnique, LLR, F-91128 Palaiseau, France
University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom
Università di Ferrara, Dipartimento di Fisica and INFN, I-44100 Ferrara, Italy
Florida A&M University, Tallahassee, FL 32307, USA
Laboratori Nazionali di Frascati dell’INFN, I-00044 Frascati, Italy
Università di Genova, Dipartimento di Fisica and INFN, I-16146 Genova, Italy
Harvard University, Cambridge, MA 02138, USA
Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany
Imperial College London, London, SW7 2AZ, United Kingdom
University of Iowa, Iowa City, IA 52242, USA
Iowa State University, Ames, IA 50011-3160, USA
Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
University of Liverpool, Liverpool L69 72E, United Kingdom
Queen Mary, University of London, E1 4NS, United Kingdom
University of London, Royal Holloway and Bedford New College, Egham, Survey TW20 0EX, United Kingdom
University of Louisville, Louisville, KY 40292, USA
University of Manchester, Manchester M13 9PL, United Kingdom
University of Maryland, College Park, MD 20742, USA
University of Massachusetts, Amherst, MA 01003, USA
Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, MA 02139, USA
McGill University, Montréal, QC, Canada H3A 2T8
Università di Milano, Dipartimento di Fisica and INFN, I-20133 Milano, Italy
University of Mississippi, University, MS 38677, USA
Université de Montréal, Laboratoire René J. A. Lévesque, Montréal, QC, Canada H3C 3J7
Mount Holyoke College, South Hadley, MA 01075, USA
Università di Napoli Federico II, Dipartimento di Scienze Fisiche and INFN, I-80126, Napoli, Italy
NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands
University of Notre Dame, Notre Dame, IN 46556, USA
Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
Ohio State University, Columbus, OH 43210, USA
University of Oregon, Eugene, OR 97403, USA
Università di Padova, Dipartimento di Fisica and INFN, I-35131 Padova, Italy
Universités Paris VI et VII, Lab de Physique Nucléaire H. E., F-75252 Paris, France
Università di Pavia, Dipartimento di Elettronica and INFN, I-27100 Pavia, Italy
University of Pennsylvania, Philadelphia, PA 19104, USA
Università di Perugia, Dipartimento di Fisica and INFN, I-06100 Perugia, Italy
Università di Pisa, Dipartimento di Fisica, Scuola Normale Superiore and INFN, I-56127 Pisa, Italy
Prairie View A&M University, Prairie View, TX 77446, USA
Princeton University, Princeton, NJ 08544, USA
Università di Roma La Sapienza, Dipartimento di Fisica and INFN, I-00185 Roma, Italy
University of Rostock, D-18051 Rostock, Germany
Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom
DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France
University of South Carolina, Columbia, SC 29208, USA
Stanford Linear Accelerator Center, Stanford, CA 94309, USA
Stanford University, Stanford, CA 94305-4060, USA
State Univ. of New York, Albany, NY 12222, USA
University of Tennessee, Knoxville, TN 37996, USA
University of Texas at Austin, Austin, TX 78712, USA
University of Texas at Dallas, Richardson, TX 75083, USA
Università di Torino, Dipartimento di Fisica Sperimentale and INFN, I-10125 Torino, Italy
Università di Trieste, Dipartimento di Fisica and INFN, I-34127 Trieste, Italy
Vanderbilt University, Nashville, TN 37235, USA
University of Victoria, Victoria, BC, Canada V8W 3P6
University of Wisconsin, Madison, WI 53706, USA
Yale University, New Haven, CT 06511, USA

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We measure the branching fractions and CP asymmetries in the decays \(B^0 \to K^+ K^- K_0^0\) and \(B^+ \to K^+ K_0^0 K_0^0\) using a sample of approximately 122 million \(B\overline{B}\) pairs collected by the BABAR detector. From a time-dependent analysis of the \(K^+ K^- K_0^0\) sample that excludes \(\phi K_0^0\), the values of the CP-violation parameters are \(S = -0.56 \pm 0.25 \pm 0.04\) and \(C = -0.10 \pm 0.19 \pm 0.10\), where the first uncertainty is statistical, the second is systematic. We confirm that the final state is nearly purely CP-even. Using this result and setting \(C = 0\), we extract the Standard Model parameter \(\sin 2\beta = 0.57 \pm 0.26 \pm 0.04\) where the last error is due to uncertainty on the CP content.

We present the first measurement of the CP-violating charge asymmetry \(A_{CP}(B^+ \to K^+ K_0^0 K_0^0) = -0.04 \pm 0.11 \pm 0.02\), with a 90\% confidence-level interval of \([-0.23, 0.15]\). The branching fractions are \(B(B^0 \to K^+ K^- K_0^0) = (23.8 \pm 2.0 \pm 1.6) \times 10^{-6}\) and \(B(B^+ \to K^+ K_0^0 K_0^0) = (10.7 \pm 1.2 \pm 1.0) \times 10^{-6}\).

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In the Standard Model (SM) of particle physics, the decays \(B^0 \to K^+ K^- K_0^0\) and \(B^+ \to K^+ K_0^0 K_0^0\) are dominated by \(b \to s \bar{s} s\) gluonic penguin diagrams. CP violation in such decays arises from the Cabibbo–Kobayashi–Maskawa (CKM) quark-mixing mechanism. Neglecting CKM-suppressed contributions, the expectation for the CP-asymmetry parameters in \(B^0 \to K^+ K^- K_0^0\) decays is the same as in \(B^0 \to J/\psi K_0^0\) decays, where CP violation has been observed. The decay rates for \(B^+ \to K^+ K_0^0 K_0^0\) and \(B^- \to K^- K_0^0 K_0^0\) are expected to be equal. However, contributions from physics beyond the SM could invalidate these predictions. Since \(b \to s \bar{s} s\) decays involve one-loop transitions, they are especially sensitive to additional contributions. Present results in decays of neutral B mesons are inconclusive due to large statistical errors. Belle measures the CP asymmetry parameter in \(\phi K_0^0\) decays of sin \(2\beta = -0.96 \pm 0.50 \pm 0.11\), which is 3.5 standard deviations from the SM expectation of sin \(2\beta = 0.731 \pm 0.056\). A BABAR measurement of sin \(2\beta = 0.47 \pm 0.34 \pm 0.08\) is consistent with the SM and disagrees with Belle by 2.3 standard deviations.

A more accurate CP measurement can be made using all the decays to \(K^+ K^- K_0^0\) that do not contain a \(\phi\) meson. This sample is several times larger than the sample of \(\phi K_0^0\) decays. As Belle noted, the CP content of the final state can be extracted using an isospin analysis. In decays that exclude \(\phi K_0^0\), Belle measures sin \(2\beta = 0.51 \pm 0.26 \pm 0.05\), consistent with the SM expectation. In this letter we present measurements of CP asymmetry and CP content in \(K^+ K^- K_0^0\) decays, and the first measurement of the charge asymmetry rate in \(B^+ \to K^+ K_0^0 K_0^0\) decays.

This analysis is based on about 122 million \(B\overline{B}\) pairs collected with the BABAR detector at the PEP-II asymmetric-energy \(e^+ e^-\) storage rings at SLAC, operating on the \(Y(4S)\) resonance. We reconstruct \(B\) mesons from \(K_0^0 \to \pi^+ \pi^-\) and \(K_\pm\) candidates. Charged kaons are distinguished from pions and protons using energy-loss (dE/dx) information in the tracking system and from the Cherenkov angle and number of photons measured by the detector of internally reflected Cherenkov light (DIRC). We accept \(K_0^0 \to \pi^+ \pi^-\) candidates that have a two-pion invariant mass within 12 MeV/c\(^2\) of the nominal \(K_0^0\) mass, a decay length greater than 3 standard deviations, and a cosine of the angle between the line connecting the \(B\) and \(K_0^0\) decay vertices and the \(K_0^0\) momentum greater than 0.999. The three daughters in the \(B\) decay are fitted constraining their paths to a common vertex, and the \(K_0^0\) mass to the nominal value.

In the characterization of the \(B\) candidates we use two kinematic variables. The energy difference \(\Delta E = E_B - \sqrt{s}/2\) is reconstructed from the energy of the \(B\) candidate \(E_B\) and the total energy \(\sqrt{s}\) in the \(e^+ e^-\) center-of-mass (CM) frame. The \(\Delta E\) resolution for signal events is 18 MeV. We also use the beam-energy-substituted mass \(m_{ES} = \sqrt{(s/2 + \vec{p}_B \cdot \vec{p}_B)^2/E_B^2 - \vec{p}_B^2}\), where \(\vec{p}_B\) is the four-momentum of the initial \(e^+ e^-\) system and \(\vec{p}_B\) is the momentum of the \(B\) candidate, both measured in the laboratory frame. The \(m_{ES}\) resolution for signal events is 2.6 MeV/c\(^2\). We retain candidates with \(|\Delta E| < 200\) MeV and \(5.2 < m_{ES} < 5.3\) GeV/c\(^2\).

The background is dominated by random combinations of tracks created in \(e^+ e^-\to q\bar{q}(q = u, d, s, c)\) continuum events. We suppress this background by utilizing the difference in the topology in the CM frame between jet-like \(q\bar{q}\) events and spherical signal events. The topology is described using angle \(\theta_T\) between the thrust axis of the \(B\) candidate and the thrust axis of the charged and neutral particles in the rest of the event (ROE). Other quantities that characterize the event topology are two sums over the ROE: \(L_0 = \sum |\vec{p}_i^*|\) and \(L_2 = \sum |\vec{p}_i^*| \cos^2 \theta_i\), where \(\theta_i\) is the angle between the momentum \(\vec{p}_i^*\) and the thrust axis of the \(B\) candidate. Additional separation is achieved using the angle \(\theta_B\) between the \(B\) momentum direction and the beam axis. After requiring \(|\cos \theta_T| < 0.9\), these four event shape variables are combined into a Fisher discriminant \(F\).

The remaining background originates from \(B\) decays where a neutral or charged pion is missed during reconstruction (peaking \(B\) background). We use Monte Carlo (MC) events to model the signal and the peaking background, and data sidebands to model continuum background.

We suppress background from \(B\) decays that proceed through a \(b \to c\) transition leading to the \(K^+ K^- K_0^0\) final state by applying invariant mass cuts to remove \(D^0 \to K K, D^+ \to K^+ K_0^0, J/\psi \to K K,\) and...
\( \chi_{0} \rightarrow KK(K_0^0K_0^0) \) decays. Finally, \( B \) decays into final states with pions are eliminated by requiring the pion misidentification rate to be less than 2%.

The time-dependent CP asymmetry is obtained by measuring the proper time difference \( \Delta t \) between a fully reconstructed neutral \( B \) meson \( (B_{\text{CP}}) \) decaying into \( K^+K^-K_0^0 \), and the partially reconstructed recoil \( B \) meson \( (B_{\text{tag}}) \). Decay products of the recoil side are used to determine the \( B_{\text{tag}} \) meson’s flavor (flavor tag) and to classify the event into five mutually exclusive tagging categories \(^4\). If the fraction of events in category \( c \) is \( \epsilon_c \) and the mistag probability is \( w_c \), the overall quality of the tagging, \( \sum_c \epsilon_c(1-2w_c)^2 \), is \((28.0 \pm 0.4)\%\).

The time difference \( \Delta t \) is extracted from the measurement of the separation \( \Delta z \) between the \( B_{\text{CP}} \) and \( B_{\text{tag}} \) vertices, along the boost axis \((z)\) of the \( B\overline{B} \) system. The vertex position of the \( B_{\text{CP}} \) meson is reconstructed primarily from kaon tracks, and its MC-estimated resolution ranges between 40–80 \( \mu \)m, depending on the opening angle and direction of the kaon pair. The final \( \Delta t \) resolution is dominated by the uncertainty on the \( B_{\text{tag}} \) vertex which allows the \( \Delta t (\Delta z) \) precision with r.m.s. of 1.1 ps (180 \( \mu \)m). We retain events that have \|\Delta t\| < 20 ps and whose estimated uncertainty \( \sigma_{\Delta t} \) is less than 2.5 ps. The \( \Delta t \) resolution function is parameterized as a sum of two Gaussian distributions whose widths are given by a scale factor times the event-by-event uncertainty \( \sigma_{\Delta t} \). A third Gaussian distribution, with a fixed large width, accounts for a small fraction of outlying events \(^4\).

Parameters describing the tagging performance and the \( \Delta t \) resolution function are extracted from approximately 30,000 \( B^0 \) decays into \( D^{(*)} \rightarrow X^+(X^+=\pi^+,\rho^+,a_1^+) \) flavor eigenstates \((B_{\text{flav}} \) sample).

The decay rate \( f_+(f_-) \) when the flavor of the tagging meson is a \( B^0 \) \((\overline{B}^0) \) is given by

\[
\begin{align*}
\mathcal{f}_\pm(\Delta t) & = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left[ 1 \pm S \sin(\Delta m_4 \Delta t) \right] \\
& \mp C \cos(\Delta m_4 \Delta t),
\end{align*}
\]

where \( \tau_{B^0} \) is the mean \( B^0 \) lifetime and \( \Delta m_4 \) is the \( B^0-\overline{B}^0 \) oscillation frequency. The parameters \( C \) and \( S \) describe the magnitude of CP violation in the decay and the interference between decay and mixing, respectively. In the SM, we expect \( C = 0 \) because there can be no direct CP violation when there is only one decay mechanism. If we exclude \( \phi K_0^0 \) events by applying a \( K^+K^- \) invariant mass cut of 15 MeV/c\(^2\) around the nominal \( \phi \) mass \(^12\), and assume that the remaining \( B_{\text{CP}} \) candidates are CP-even, as our analysis below indicates, we expect \( S = -\sin 2\beta = -0.731 \pm 0.056 \) \(^{11,5}\).

Direct CP violation in \( B^+ \rightarrow K^+K_0^0K_0^0 \) decays is measured as an asymmetry in the decay rates

\[
\mathcal{A}_{\text{CP}} = \frac{\Gamma_{K^-K_0^0K_0^0} - \Gamma_{K^+K_0^0K_0^0}}{\Gamma_{K^-K_0^0K_0^0} + \Gamma_{K^+K_0^0K_0^0}},
\]

The SM expectation for \( \mathcal{A}_{\text{CP}} \) is zero.

Branching fractions and CP asymmetries are extracted in unbinned extended maximum likelihood fits to the different samples. The likelihood function \( \mathcal{L} \), with event yields \( N_i \) and probability density functions (PDFs) \( P_{i,j} \), is:

\[
\mathcal{L} = \exp \left( -\sum_i N_i \prod_{j=1} \left[ \sum_i N_i P_{i,j} \right] \right)
\]

where \( j \) runs over events and \( i \) over event yields. We have a total of 6144 events in the \( K^+K^-K_0^0 \) mode, and 13864 (12862) in the \( K^+K^-K_0^0 \) mode with \( \phi K_0^0 \) included (excluded).

In the measurement of the branching fractions \( B \), the total PDF is formed as \( P(m_{\text{ES}}) \cdot P(\Delta E) \cdot P(\mathcal{F}). \) Event yields for signal, continuum, and peaking \( B \) background are varied in the fit. In the extraction of the charge asymmetry \( \mathcal{A}_{\text{CP}} \) in \( K^+K_0^0K_0^0 \) decays, the yields are split by the charge, which brings the total number of varied parameters to six. To extract the branching fractions, we assign a weight for each event to belong to the signal decay, \( W_j = \frac{\sum_i V_{i,j} P_{i,j}}{\sum_i V_{i,j} P_{i,j}} \) where \( V_{s,i} \) is the signal row of the covariance matrix obtained from the fit \(^{14}\). The branching fraction is calculated as \( \mathcal{B} = \sum_j W_j / \varepsilon_j \). Since the efficiency \( \varepsilon_j \) varies across the phase space, \( \varepsilon_j \) is computed in small phase-space bins using simulated events. The method is cross-checked with a simple counting analysis. Distributions of \( m_{\text{ES}} \) and \( \Delta E \) are shown in Fig. \(^{11}\) and the fit results are given in Table \(^{11}\).

![FIG. 1](image-url)  
**FIG. 1:** Projection plots of the variables \( m_{\text{ES}} \) (a, c) and \( \Delta E \) (b, d) in the fits for \( B^0 \rightarrow K^+K^-K_0^0 \) (top) and \( B^+ \rightarrow K^+K_0^0K_0^0 \) (bottom) decays. The points are data and the curves are projections from the likelihood fit. The signal-to-background ratio is enhanced with a cut on the event probability.

In the time-dependent CP fit, \( K^+K^-K_0^0 \) events that exclude \( \phi K_0^0 \) decays are fit simultaneously with the \( B_{\text{flav}} \) sample. The PDFs are formed as \( P(m_{\text{ES}}) \cdot P(\Delta E) \cdot P(\mathcal{F}) \cdot P_{\text{CP}}(\Delta t; \sigma_{\Delta t}) \) for \( B_{\text{CP}} \) events and \( P(m_{\text{ES}}) \cdot P_{\text{CP}}(\Delta t; \sigma_{\Delta t}) \) in
TABLE I: Summary of branching fraction (B), time-dependent (S, C) and direct CP-asymmetry (ACp) results. Nsig and ε are the signal yield and the average total efficiency in the branching-fraction fit; feven is the CP-even fraction of the final states. The 90% confidence-level interval for ACp is [−0.23, 0.15].

| Mode | ε (%) | Nsig | B (10⁻⁶) | feven | S | C | ACp |
|------|-------|------|----------|-------|---|---|-----|
| K⁺K⁻K⁰ | 8.58  | 201 ± 16 | 20.2 ± 1.9 ± 1.4 | 0.98 ± 0.15 ± 0.04 | −0.56 ± 0.25 ± 0.04 | −0.10 ± 0.19 ± 0.10 | — |
| K⁺K⁻K⁰ all | 8.78  | 249 ± 20 | 23.8 ± 2.0 ± 1.6 | 0.83 ± 0.12 ± 0.03 | — | — | — |
| K⁺K⁰K⁺S⁻ | 9.7   | 122 ± 14 | 10.7 ± 1.2 ± 1.0 | — | −0.16 ± 0.35 | −0.08 ± 0.22 | −0.04 ± 0.11 ± 0.02 |

CP excludes φK⁰ events.

The results listed in Table I are in agreement with Belle’s measurements of 0.86 ± 0.15 ± 0.05 and 1.04 ± 0.19 ± 0.06 for the total sample and the CP sample that excludes φK⁰ events, respectively. We estimate the fraction of remaining φK⁰ events in the CP sample, using a non-interfering Breit-Wigner for the φ shape and measured branching fractions, to be 1.1 ± 0.4%. As a consistency check, we examine the distribution of the cosine of the helicity angle θH, which is defined as the angle between the K⁺ and B⁰ directions in the K⁺K⁻ center of mass frame. The distribution in several K⁺K⁻ invariant mass bins of the CP sample is approximately uniform which is consistent with S-wave decays. The presence of interference effects due to CP-odd amplitudes cannot be ruled out, but this would require a full amplitude analysis which is not feasible with the present statistics.

If we account for a small CP-odd fraction in the CP sample, we can extract the SM parameter sin2β. In a fit with C = 0 we get sin2β = −S/(2feven − 1) = 0.57 ± 0.26 ± 0.04 ± 0.17 where the last error is due to uncertainty on the CP content.

FIG. 2: Plots a) and b) show the Δt distributions of B⁰- and B⁻-tagged K⁺K⁻K⁰ events. The solid lines refer to the fit for all events; the dashed lines correspond to the background. Plot c) shows the raw asymmetry, where the solid line is obtained from the fit and the dotted line is the SM expectation for the measured CP content. The signal-to-background ratio is enhanced with a cut on the event probability.

Results of the time-dependent CP asymmetry measurement in K⁺K⁻K⁰ are given in Table I. Figure 2 shows the Δt distributions of events with B⁰ and B⁻ tags, with projections from the likelihood fit superimposed. The fit procedure is verified with the K⁺K⁰K⁰ sample (Table II), where one expects zero asymmetry, and the J/ψK⁰ sample where the results are consistent with our previous measurement [10].

We evaluate the fraction feven of CP-even final states in B⁰ → K⁺K⁻K⁰ decays by comparing K⁺K⁻K⁰ and K⁺K⁰K⁰ decay rates: feven = 2Γ(B⁺→K⁺K⁻K⁰)/Γ(B⁰→K⁺K⁻K⁰) [10].

Systematic uncertainties in the branching fraction measurements are given in Table II. We include contributions from the signal reconstruction efficiency and from the modeling of the efficiency variation over the phase space. Other errors come from the fit bias, the counting of B⁻B⁻ pairs, and the misidentification of kaons. We assume equal production rates of B⁺B⁻ and B⁺B⁻. The systematic uncertainty on ACp due to charge asymmetry in track finding and identification is 0.02.

The systematic errors on the time-dependent CP-asymmetry parameters are given in Table II. The errors account for the fit bias, the presence of double CKM-suppressed decays (DCSD) in B⁻tag [15], uncertainty in the beam spot and detector alignment, and the asymmetry in...
the tagging efficiency for signal and background events. Other smaller effects come from $\Delta t$ resolution, PDF parameterization of yield variables, and uncertainty on the $B^0$ lifetime and mixing frequency. In the fit we use $T_{CP} = 1.537 \pm 0.015$ ps and $\Delta m_d = 0.502 \pm 0.007$ ps$^{-1}$.

In summary, we have measured branching fractions for charmless decays of $B$ mesons into the three-body final states $B^0 \to K^+K^-K^0$ and $B^+ \to K^+K^0_sK^0_s$. Using two independent approaches, we find that the $K^+K^-K^0_s$ final state is dominated by a $CP$-even component. The results agree with previous measurements [9, 10]. In the first measurement of the charge asymmetry in $B^+ \to K^+K^0_sK^0_s$ decays, we find no evidence for direct $CP$ violation. We measure a time-dependent $CP$ asymmetry in $B^0 \to K^+K^-K^0_s$ decays at the 1.9σ level. The obtained sin 2$\beta$ is consistent with the SM expectation and previous measurements in decays into the $K^+K^-K^0_s$ final state [7, 8], but differs from Belle’s measurement in $\phi K^0_s$ decays [9] by 2.7 standard deviations.

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* Now at Department of Physics, University of Warwick, Coventry, United Kingdom
† Also with Università della Basilicata, Potenza, Italy
‡ Also with IFIC, Instituto de Física Corpuscular, CSIC-Universidad de Valencia, Valencia, Spain
§ Deceased
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We measure the branching fractions and $CP$ asymmetries in the decays $B^0 \to K^+K^-K_S$ and $B^+ \to K^+K_SK_S$ using a sample of approximately 122 million $BB$ pairs collected by the BaBar detector. From a time-dependent analysis of the $K^+K^-K_S$ sample that excludes $\phi K_S$, the values of the $CP$-violation parameters are $S = -0.56 \pm 0.25 \pm 0.04$ and $C = -0.10 \pm 0.19 \pm 0.10$, where the first uncertainty is statistical, the second is systematic. We confirm that the final state is nearly purely $CP$-even. Using this result and setting $C = 0$, we extract the Standard Model parameter $\sin 2\beta = 0.57 \pm 0.26 \pm 0.04^{+0.17}_{-0}$ where the last error is due to uncertainty on the $CP$ content. We present the first measurement of the $CP$-violating charge asymmetry $A_{CP}(B^+ \to K^+K_SK_S) = -0.04 \pm 0.11 \pm 0.02$, with a 90% confidence-level interval of $[-0.23, 0.15]$. The branching fractions are $\mathcal{B}(B^0 \to K^+K^-K^0) = (23.8 \pm 2.0 \pm 1.6) \times 10^{-6}$ and $\mathcal{B}(B^+ \to K^+K_SK_S) = (10.7 \pm 1.2 \pm 1.0) \times 10^{-6}$. 
