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Search for the decay $B^0 \to p\bar{p}$

B. Aubert,[1] R. Barate,[1] D. Boutigny,[1] F. Couderc,[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. Pompili,[2] J. C. Chen,[3] N. D. Qi,[3] G. Rong,[3] P. Wang,[3] Y. S. Zhu,[3] G. Eigen,[4] I. Ofte,[4] B. Stugu,[4] G. S. Abrams,[5] A. W. Borgland,[5] A. B. Breon,[5] D. N. Brown,[5] J. Button-Shafer,[5] R. N. Cahn,[5] E. Charles,[5] C. T. Day,[5] M. S. Gill,[5] A. V. Gritsan,[5] Y. Groysman,[5] R. G. Jacobsen,[5] R. W. Kadel,[5] J. Kadyk,[5] L. T. Kerth,[5] Yu. G. Kolomensky,[5] G. Kukartsev,[5] C. LeClerc,[5] G. Lynch,[5] A. M. Merchant,[5] L. M. Mir,[5] P. J. Oddone,[5] T. J. Orimoto,[5] M. Pripstein,[5] N. A. Roe,[5] M. T. Ronan,[5] V. G. Shelkov,[5] W. A. Wenzel,[5] K. Ford,[6] T. J. Harrison,[6] C. M. Hawkes,[6] S. E. Morgan,[6] A. T. Watson,[6] M. Fritsch,[7] K. Goetzen,[7] T. Held,[7] H. Koch,[7] B. Lewandowski,[7] M. Pelizaeus,[7] M. Steinke,[7] J. T. Boyd,[8] N. Chevalier,[8] W. N. Cottingham,[8] M. P. Kelly,[8] 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] A. D. Bukin,[11] V. P. Druzhinin,[11] V. B. Golubev,[11] V. N. Ivanchenko,[11] E. A. Kravchenko,[11] A. P. Onuchin,[11] S. I. Serednyakov,[11] Yu. I. Skovpen,[11] E. P. Solodov,[11] A. N. Yushkov,[11] D. Best,[12] M. Bruinsma,[12] M. Chao,[12] I. Eschrich,[12] D. Kirkby,[12] A. J. Lankford,[12] M. Mandelkern,[12] R. K. Mommsen,[12] W. Roethel,[12] D. P. Stoker,[12] C. Buchanan,[13] B. L. Hartfiel,[13] 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. W. Berryhill,[16] C. Campagnari,[16] B. Dahmes,[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. Dvoretskii,[18] D. G. Hitlin,[18] I. Narsky,[18] T. Piatenko,[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. Olivas,[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] T. Colberg,[22] M. Dickopp,[22] E. Feltresi,[22] A. Hauke,[22] H. M. Lacker,[22] E. Maly,[22] R. Müller-Pfefferkorn,[22] R. Nogowski,[22] S. Otto,[22] A. Petzold,[22] J. Schubert,[22] K. R. Schubert,[22] R. Schwierz,[22] B. Spaan,[22] J. E. Sundermann,[22] D. Bernard,[23] G. R. Bonneaud,[23] F. Brochard,[23] P. Grenier,[23] S. Schrenk,[23] Ch. Thiebaux,[23] G. Vasileiadis,[23] M. Verderi,[23] D. J. Bard,[24] P. J. Clark,[24] D. Lavin,[24] F. Muheim,[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. Treadwell,[26] R. Baldini-Ferroli,[27] A. Calcaterra,[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] 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. Yi,[33] 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. Plaszczynski,[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] J. P. Coleman,[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. Cormack,[37] P. F. Harrison,[37,*] G. B. Mohanty,[37] C. L. Brown,[38] G. Cowan,[38] R. L. Flack,[38] H. U. Flaecher,[38] M. G. Green,[38] C. E. Marker,[38] T. R. McMahon,[38] S. Ricciardi,[38] F. Salvatore,[38] G. Vaitsas,[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. Lae,[41] V. Lillard,[41] D. A. Roberts,[41] G. Blaylock,[42] C. Dallapiccola,[42] K. T. Flood,[42] S. S. Hertzbach,[42] R. Kofler,[42] V. B. Koptchev,[42] T. B. Moore,[42] S. Saremi,[42] H. Staengle,[42] S. Willocq,[42] R. Cowan,[43] G. Sciolla,[43] F. Taylor,[43] R. K. Yamamoto,[43] D. J. J. Mangeol,[44] P. M. Patel,[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,†] C. Gatto,[49] L. Lista,[49] D. Monorchio,[49] P. Paolucci,[49] D. Piccolo,[49] C. Sciacca,[49] M. Baak,[50] H. Bulten,[50] G. Raven,[50] L. Wilden,[50] C. P. Jessop,[51] J. M. LoSecco,[51] T. A. Gabriel,[52] T. Allmendinger,[53] B. Brau,[53] K. K. Gan,[53] K. Honscheid,[53] D. Hufnagel,[53] H. Kagan,[53] R. Kass,[53] T. Pulliam,[53] A. M. Rahimi,[53] R. Ter-Antonyan,[53] Q. K. Wong,[53] J. Brau,[54] R. Frey,[54] O. Igonkina,[54] C. T. Potter,[54] N. B. Sinev,[54] D. Strom,[54] E. Torrence,[54] F. Colecchia,[55] A. Dorigo,[55] F. Galeazzi,[55] M. Margoni,[55] M. Morandin,[55] M. Posocco,[55] M. Rotondo,[55] F. Simonetto,[55] R. Stroili,[55] G. Tiozzo,[55] C. Voci,[55] M. Benayoun,[56] H. Briand,[56] J. Chauveau,[56] P. David,[56] Ch. de la Vaissière,[56] L. Del Buono,[56] O. Hamon,[56] M. J. J. John,[56] Ph. Leruste,[56] J. Ocariz,[56] M. Pivk,[56] L. Roos,[56] S. T'Jampens,[56] G. Therin,[56] P. F. Manfredi,[57] V. Re,[57] P. K. Behera,[58] L. Gladney,[58] Q. H. Guo,[58] J. Panetta,[58] F. Anulli,[27,59] M. Biasini,[59] I. M. Peruzzi,[27,59] M. Pioppi,[59] C. Angelini,[60] G. Batignani,[60] S. Bettarini,[60] M. Bondioli,[60] F. Bucci,[60] G. Calderini,[60] M. Carpinelli,[60] V. Del Gamba,[60] F. Forti,[60] M. A. Giorgi,[60] A. Lusiani,[60] G. Marchiori,[60] F. Martinez-Vidal,[60,‡] M. Morganti,[60] N. Neri,[60] E. Paoloni,[60] M. Rama,[60] G. Rizzo,[60] F. Sandrelli,[60] J. Walsh,[60] M. Haire,[61] D. Judd,[61] K. Paick,[61] D. E. Wagoner,[61] N. Danielson,[62] P. Elmer,[62] Y. P. Lau,[62] C. Lu,[62] V. Miftakov,[62] J. Olsen,[62] A. J. S. Smith,[62] A. V. Telnov,[62] F. Bellini,[63] G. Cavoto,[62,63] R. Faccini,[63] F. Ferrarotto,[63] F. Ferroni,[63] M. Gaspero,[63] L. Li Gioi,[63] M. A. Mazzoni,[63] S. Morganti,[63] M. Pierini,[63] G. Piredda,[63] F. Safai Tehrani,[63] C. Voena,[63] S. Christ,[64] G. Wagner,[64] R. Waldi,[64] T. Adye,[65] N. De Groot,[65] B. Franek,[65] N. I. Geddes,[65] G. P. Gopal,[65] E. O. Olaiya,[65] R. Aleksan,[66] S. Emery,[66] A. Gaidot,[66]

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S. F. Ganzhur,[66] P.-F. Giraud,[66] G. Hamel de Monchenault,[66] W. Kozanecki,[66] M. Langer,[66] M. Legendre,[66] G. W. London,[66] B. Mayer,[66] G. Schott,[66] G. Vasseur,[66] Ch. Yèche,[66] M. Zito,[66] M. V. Purohit,[67] A. W. Weidemann,[67] F. X. Yumiceva,[67] D. Aston,[68] R. Bartoldus,[68] N. Berger,[68] A. M. Boyarski,[68] O. L. Buchmueller,[68] M. R. Convery,[68] M. Cristinziani,[68] G. De Nardo,[68] D. Dong,[68] J. Dorfan,[68] D. Dujmic,[68] W. Dunwoodie,[68] E. E. Elsen,[68] S. Fan,[68] R. C. Field,[68] T. Glanzman,[68] S. J. Gowdy,[68] T. Hadig,[68] V. Halyo,[68] C. Hast,[68] T. Hryn'ova,[68] W. R. Innes,[68] M. H. Kelsey,[68] P. Kim,[68] M. L. Kocian,[68] D. W. G. S. Leith,[68] J. Libby,[68] S. Luitz,[68] V. Luth,[68] H. L. Lynch,[68] H. Marsiske,[68] R. Messner,[68] D. R. Muller,[68] C. P. O'Grady,[68] V. E. Ozcan,[68] A. Perazzo,[68] M. Perl,[68] S. Petrak,[68] B. N. Ratcliff,[68] A. Roodman,[68] A. A. Salnikov,[68] R. H. Schindler,[68] J. Schwiening,[68] G. Simi,[68] A. Snyder,[68] A. Soha,[68] J. Stelzer,[68] D. Su,[68] M. K. Sullivan,[68] J. Va'vra,[68] S. R. Wagner,[68] M. Weaver,[68] A. J. R. Weinstein,[68] W. J. Wisniewski,[68] M. Wittgen,[68] D. H. Wright,[68] A. K. Yarritu,[68] C. C. Young,[68] P. R. Burchat,[69] A. J. Edwards,[69] T. I. Meyer,[69] B. A. Petersen,[69] C. Roat,[69] S. Ahmed,[70] M. S. Alam,[70] J. A. Ernst,[70] M. A. Saeed,[70] M. Saleem,[70] F. R. Wappler,[70] W. Bugg,[71] M. Krishnamurthy,[71] S. M. Spanier,[71] R. Eckmann,[72] H. Kim,[72] J. L. Ritchie,[72] A. Satpathy,[72] R. F. Schwitters,[72] J. M. Izen,[73] I. Kitayama,[73] X. C. Lou,[73] S. Ye,[73] F. Bianchi,[74] M. Bona,[74] F. Gallo,[74] D. Gamba,[74] C. Borean,[75] L. Bosisio,[75] C. Cartaro,[75] F. Cossutti,[75] G. Della Ricca,[75] S. Dittongo,[75] S. Grancagnolo,[75] L. Lanceri,[75] P. Poropat,[75,§] L. Vitale,[75] G. Vuagnin,[75] R. S. Panvini,[76] Sw. Banerjee,[77] C. M. Brown,[77] D. Fortin,[77] P. D. Jackson,[77] R. Kowalewski,[77] J. M. Roney,[77] H. R. Band,[78] S. Dasu,[78] M. Datta,[78] A. M. Eichenbaum,[78] M. Graham,[78] J. J. Hollar,[78] J. R. Johnson,[78] P. E. Kutter,[78] H. Li,[78] R. Liu,[78] F. Di Lodovico,[78] A. Mihalyi,[78] A. K. Mohapatra,[78] Y. Pan,[78] R. Prepost,[78] A. E. Rubin,[78] S. J. Sekula,[78] P. Tan,[78] J. H. von Wimmersperg-Toeller,[78] J. Wu,[78] S. L. Wu,[78] Z. Yu,[78] and H. Neal[79]

(BABAR Collaboration)

[1]*Laboratoire de Physique des Particules, F-74941 Annecy-le-Vieux, France*
[2]*Università di Bari, Dipartimento di Fisica and INFN, I-70126 Bari, Italy*
[3]*Institute of High Energy Physics, Beijing 100039, China*
[4]*University of Bergen, Inst. 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 Dresden, Institut für Kern und Teilchenphysik, D-01062 Dresden, Germany*
[23]*Ecole Polytechnique, LLR, F-91128 Palaiseau, France*
[24]*University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom*
[25]*Università di Ferrara, Dipartimento di Fisica and INFN, I-44100 Ferrara, Italy*
[26]*Florida A&M University, Tallahassee, Florida 32307, USA*
[27]*Laboratori Nazionali di Frascati dell'INFN, I-00044 Frascati, Italy*
[28]*Università di Genova, Dipartimento di Fisica and INFN, I-16146 Genova, Italy*
[29]*Harvard University, Cambridge, Massachusetts 02138, USA*
[30]*Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany*
[31]*Imperial College London, London, SW7 2AZ, United Kingdom*
[32]*University of Iowa, Iowa City, Iowa 52242, USA*
[33]*Iowa State University, Ames, Iowa 50011-3160, USA*
[34]*Laboratoire de l'Accélérateur Linéaire, F-91898 Orsay, France*
[35]*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
[36]*University of Liverpool, Liverpool L69 72E, United Kingdom*
[37]*Queen Mary, University of London, E1 4NS, United Kingdom*
[38]*University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom*
[39]*University of Louisville, Louisville, Kentucky 40292, USA*

[40]*University of Manchester, Manchester M13 9PL, United Kingdom*
[41]*University of Maryland, College Park, Maryland 20742, USA*
[42]*University of Massachusetts, Amherst, Massachusetts 01003, USA*
[43]*Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA*
[44]*McGill University, Montréal, Quebec, Canada H3A 2T8*
[45]*Università di Milano, Dipartimento di Fisica and INFN, I-20133 Milano, Italy*
[46]*University of Mississippi, University, Mississippi 38677, USA*
[47]*Université de Montréal, Laboratoire René J. A. Lévesque, Montréal, Quebec, Canada H3C 3J7*
[48]*Mount Holyoke College, South Hadley, Massachusetts 01075, USA*
[49]*Università di Napoli Federico II, Dipartimento di Scienze Fisiche and INFN, I-80126, Napoli, Italy*
[50]*NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands*
[51]*University of Notre Dame, Notre Dame, Indiana 46556, USA*
[52]*Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
[53]*Ohio State University, Columbus, Ohio 43210, USA*
[54]*University of Oregon, Eugene, Oregon 97403, USA*
[55]*Università di Padova, Dipartimento di Fisica and INFN, I-35131 Padova, Italy*
[56]*Universités Paris VI et VII, Lab de Physique Nucléaire H. E., F-75252 Paris, France*
[57]*Università di Pavia, Dipartimento di Elettronica and INFN, I-27100 Pavia, Italy*
[58]*University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA*
[59]*Università di Perugia, Dipartimento di Fisica and INFN, I-06100 Perugia, Italy*
[60]*Università di Pisa, Dipartimento di Fisica, Scuola Normale Superiore and INFN, I-56127 Pisa, Italy*
[61]*Prairie View A&M University, Prairie View, Texas 77446, USA*
[62]*Princeton University, Princeton, New Jersey 08544, USA*
[63]*Università di Roma La Sapienza, Dipartimento di Fisica and INFN, 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]*Università di Torino, Dipartimento di Fisica Sperimentale and INFN, I-10125 Torino, Italy*
[75]*Università di Trieste, Dipartimento di Fisica and INFN, I-34127 Trieste, Italy*
[76]*Vanderbilt University, Nashville, Tennessee 37235, USA*
[77]*University of Victoria, Victoria, British Columbia, Canada V8W 3P6*
[78]*University of Wisconsin, Madison, Wisconsin 53706, USA*
[79]*Yale University, New Haven, Connecticut 06511, USA*

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We present the result of a search for the charmless two-body baryonic decay $B^0\to p\overline{p}$ in a sample of 88 million $\Upsilon(4S)\to B\overline{B}$ decays collected by the BABAR detector at the SLAC PEP-II asymmetric-energy B Factory. We use Cherenkov radiation to identify protons cleanly, and determine the signal yield with a maximum-likelihood fit technique using kinematic and topological information. We find no evidence for a signal and place a 90% confidence-level upper limit of $\mathcal{B}(B^0\to p\overline{p}) < 2.7\times10^{-7}$.

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We report the result of a search for the charmless two-body baryonic decay $B^0\to p\overline{p}$ [1]. Although B mesons have recently been observed to decay into several charmless three-body baryonic final states [2], there is currently no evidence for the corresponding charmless two-body decays. Previous searches [3,4] for $B^0\to p\overline{p}$ decays have yielded upper limits on the branching fraction at the level of 10^{-6}, which is consistent with calculations based on QCD sum rules [5] and the pole model [6]. A simple scaling of the measured branching

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*Presently 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.

fraction for $B^0 \to \Lambda_c^- p$ [7] by the current estimate [8] of $|V_{\rm ub}/V_{\rm cb}|^2$ leads to a prediction of charmless two-body branching fractions at the level of 10^{-7}, which is near the current sensitivity of present experiments.

The data sample used for this search contains $(87.9 \pm 1.0) \times 10^6$ $\Upsilon(4S) \to B\overline{B}$ decays collected by the BABAR detector [9] at the SLAC PEP-II e^+e^- asymmetric-energy storage ring. The primary detector components used in the analysis are a charged-particle tracking system consisting of a five-layer silicon vertex detector and a 40-layer drift chamber surrounded by a 1.5-T solenoidal magnet, and a dedicated particle identification system consisting of a detector of internally reflected Cherenkov light (DIRC).

Two-body B decays are reconstructed from pairs of oppositely-charged tracks originating from the interaction region and having momentum greater than 100 MeV/c in the direction transverse to the beam line. We require each track to have an associated Cherenkov angle (θ_c) measurement with at least four signal photons detected in the DIRC. To suppress combinatorial background arising from Λ decays, we require that the two tracks form a vertex with probability greater than 10^{-3}.

Signal candidates are identified kinematically with two variables: the difference ΔE between the center-of-mass (CM) energy of the B candidate and $\sqrt{s}/2$, where $\sqrt{s}$ is the total CM energy, and the beam-energy substituted mass $m_{\rm ES} = \sqrt{(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - \mathbf{p}_B^2}$, with the B-candidate momentum $\mathbf{p_B}$ and the four-momentum of the initial state $(E_i, \mathbf{p_i})$ defined in the laboratory frame. For signal decays, ΔE peaks near zero with a resolution of about 23 MeV, while $m_{\rm ES}$ peaks near the B mass with a resolution of about 2.6 MeV/c^2. We require $5.20 < m_{\rm ES} < 5.29\ {\rm GeV}/c^2$ and $|\Delta E| < 100$ MeV.

Protons are identified based on the θ_c measurement from the DIRC and the momentum measurement from the tracking system. Figure 1 shows the difference between measured and expected values of θ_c for the proton hypothesis, divided by the error σ_{θ_c}, for tracks from $B^0 \to p\overline{p}$ candidates in the sideband region $5.20 < m_{\rm ES} < 5.26\ {\rm GeV}/c^2$. Protons peak near zero and are well separated from the much larger background of pions and kaons. We require a θ_c measurement within $5\sigma_{\theta_c}$ of the expected value for a proton, which removes over 97% of the combinatorial background while retaining more than 91% of the signal decays (the efficiency is less than 100% due to the presence of non-Gaussian tails in the pull distribution).

We measure the efficiency of the θ_c selection in a sample of $\Lambda \to p\pi^-$ decays reconstructed in 9.6 fb^{-1} of e^+e^- annihilation data recorded 40 MeV below the $\Upsilon(4S)$ resonance. The sample is selected using kinematic and decay-vertex information, and has a purity of 98.5%. For consistency with $B^0 \to p\overline{p}$ decays, we require the proton CM momentum p^* to be in the range $2.2 < p^* < 2.8\ {\rm GeV}/c$.

Due to the unique topology and kinetics of the two-body final state, $b \to c$ decays do not populate the signal region for $B^0 \to p\overline{p}$, and backgrounds from $b \to u$ decays are negligible after the proton selection. We verify both assertions by analyzing a sample of approximately 80 fb^{-1} of $\Upsilon(4S) \to B\overline{B}$ Monte Carlo simulated events in which the B mesons decay according to the world-average branching fractions [8], and a second sample corresponding to approximately 200 fb^{-1} where one B meson in each event is forced to decay to a charmless final state. No event passes the above selection requirements in either sample.

The dominant background is from random combinations of protons produced in the process $e^+e^- \to q\overline{q}$ $(q = u, d, s)$. We verify in Monte Carlo samples that the background from the process $e^+e^- \to c\overline{c}$ is negligible compared to light-quark production. In contrast to the spherical topology of $B\overline{B}$ events, particles produced in light-quark events tend to lie near the thrust axis of the original $q\overline{q}$ pair. To suppress this background, we calculate the angle θ_S between the sphericity axis of the B candidate and the sphericity axis of the remaining particles in the event, and require $|\cos\theta_S| < 0.9$. This requirement removes 70% of the combinatorial background, while retaining 85% of the signal decays. In addition, we define a Fisher discriminant $\mathcal{F}$ [10], which is a sum of two discriminating variables with coefficients optimized to separate signal and light-quark events. The first variable is the scalar sum of the CM momenta of all the particles in the event, excluding the two tracks from the $B^0 \to p\overline{p}$ candidate. The second variable is the product $p^*(\cos\theta^*)^2$ summed over all particles (excluding the B-candidate tracks), where θ^* is the angle between its momentum and the B-candidate thrust axis in the CM frame.

The total efficiency for all of the above selection criteria is $(35.8 \pm 3.7)\%$, where the error includes the statistical and systematic uncertainties added in quadrature. The dominant source of the uncertainty is due to the limited statistical precision of the Λ control sample after applying the proton p^* constraint. A total of 804 events satisfy the $B^0 \to p\overline{p}$ selection criteria.

The signal yield is determined from a maximum likeli-

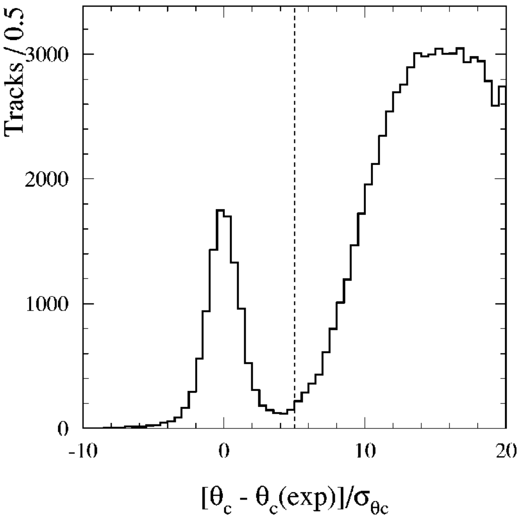

FIG. 1. The difference between the measured and expected values of θ_c, divided by the error, for tracks from $B^0 \to p\overline{p}$ candidates in the region $5.20 < m_{\rm ES} < 5.26\ {\rm GeV}/c^2$. We only use tracks that lie on the left-hand side of the dashed line.

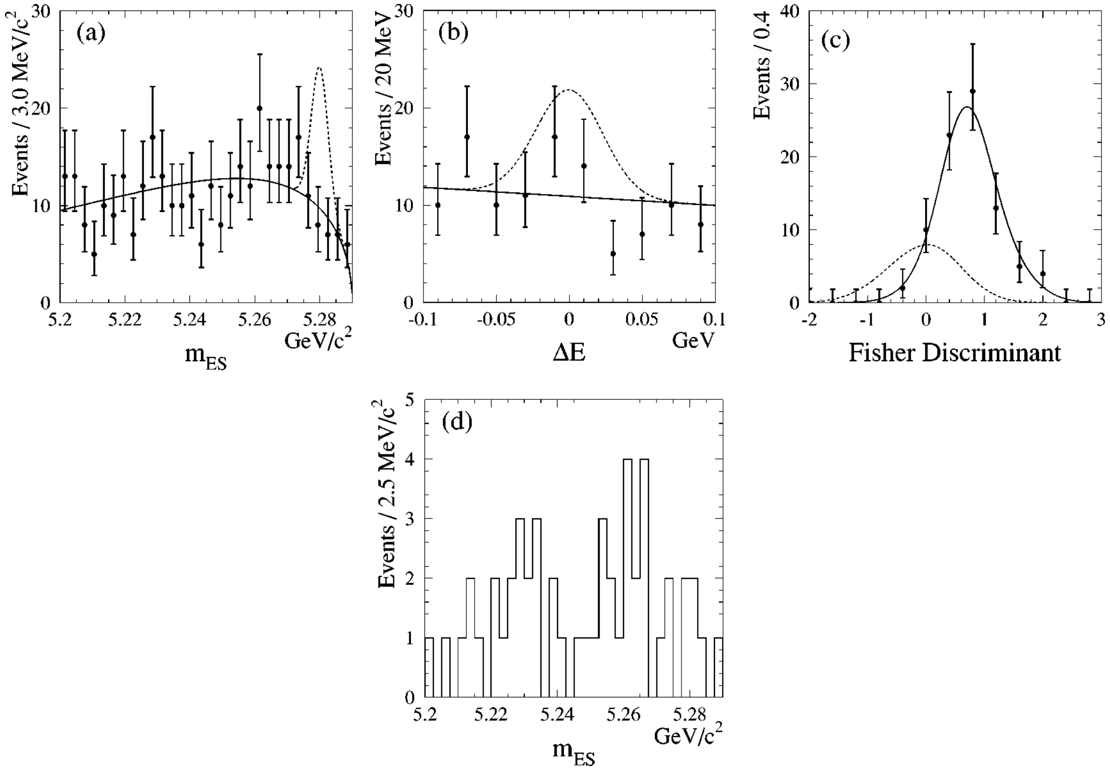

FIG. 2. Data (points with errors) and the result of the maximum likelihood fit (solid line) projected onto the (a) m_{ES}, (b) ΔE, and (c) $\mathcal{F}$ variables after applying further requirements to isolate the signal region (see text). The dashed line in (a) and (b) indicates what a signal contribution of 31.5 events (corresponding to a branching fraction of 1×10^{-6}) would look like when added to the existing background, while the dashed line in (c) shows the signal PDF for $\mathcal{F}$ normalized to 31.5 events. Plot (d) shows the distribution of m_{ES} for events in the signal-enhanced sample defined by the requirements $|\cos\theta_{\mathrm{S}}|<0.7$ and $|\Delta E|<30$ MeV.

hood fit that uses m_{ES}, ΔE, and $\mathcal{F}$ as discriminating variables. The likelihood for the sample is defined as

$$\mathcal{L}=e^{-(N_{\mathrm{S}}+N_{\mathrm{B}})}\prod_{i=1}^{N}\left[N_{\mathrm{S}}\mathcal{P}_{\mathrm{S}}^{i}+N_{\mathrm{B}}\mathcal{P}_{\mathrm{B}}^{i}\right], \qquad (1)$$

where N is the total number of events in the sample, N_{S} and N_{B} are the signal (S) and background (B) yields, and $\mathcal{P}_{\mathrm{S}}^{i}$ and $\mathcal{P}_{\mathrm{B}}^{i}$ are the signal and background probability density functions (PDFs) evaluated for event i. The PDFs are calculated from the product of PDFs for the individual variables, which are taken to be uncorrelated in the fit. We verify this assumption by calculating the linear correlation coefficient for each pair of variables. The largest correlation (−13%) is between m_{ES} and ΔE in signal decays, and we have confirmed that the effect of this small correlation is negligible. The signal yield is determined by minimizing the function $-2\ln\mathcal{L}$ with respect to N_{S} and N_{B}.

TABLE I. Summary of absolute systematic uncertainties on N_{S} from variations in the PDF parameters. The total uncertainty is the sum in quadrature of the individual contributions.

Source	Positive variation	Negative variation
Signal		
m_{ES}	+0.11	−0.62
ΔE	+0.39	−0.37
$\mathcal{F}$	+0.03	−0.03
Background		
m_{ES}	+0.32	−0.30
ΔE	+0.01	−0.01
$\mathcal{F}$	+0.86	−0.85
Total	+1.00	−1.16

We use data and Monte Carlo samples to model the PDF shapes for signal decays. The mean and resolution of m_{ES} are dominated by the beam energy, and are therefore similar in decay modes where the momentum resolution of the B candidate is significantly better than the resolution on the beam energy. We obtain the mean and resolution of m_{ES}, and also the mean of ΔE, from a large sample of $B^- \rightarrow D^0(K^-\pi^+)\pi^-$ decays reconstructed in data. Due to the difference in momentum resolution between protons and mesons, the resolution on ΔE is different for $p\overline{p}$ and $D^0\pi^-$ decays. We therefore use the value obtained in a large Monte Carlo sample of $B^0 \rightarrow p\overline{p}$ decays, and apply a 5% correction to account for the observed difference in ΔE resolution for $D^0\pi^-$ decays reconstructed in data and Monte Carlo samples. For $\mathcal{F}$ we use an asymmetric gaussian function with parameters obtained from simulated events. The shapes of the background PDFs are obtained from data in the sideband regions $100<|\Delta E|<200$ MeV and $5.20<m_{\mathrm{ES}}<5.26$ GeV/c^2. We use a linear shape for ΔE, a double-

Gaussian function for $\mathcal{F}$, and an empirical threshold function for m_{ES} [11].

Several cross-checks are performed to validate the fitting technique. To confirm that the signal yield is unbiased, we generate and fit a large set of pseudoexperiments where signal and background events are generated randomly from the PDFs. For these studies, we assume a branching fraction of 10^{-6} and find that the fitted signal yield is unbiased. We also check for biases arising from kinematic correlations by mixing Monte Carlo signal events with backgrounds generated directly from the PDFs. No significant biases are observed. The sensitivity of the analysis is determined from a set of pseudo-experiments with assumed branching fractions in the range $(0.1-1.2)\times10^{-6}$. We find that for any branching fraction above 0.5×10^{-6}, the null hypothesis would be excluded with a probability greater than 99.997%, corresponding to a significance of 5σ for a gaussian distribution.

The result of the fit is $N_{\mathrm{S}}=-0.3^{+3.1}_{-2.0}$, consistent with no signal. We determine a Bayesian 90% confidence-level (C.L.) upper limit on N_{S} by finding the value $N_{\mathrm{S}}^{\mathrm{UL}}$ such that

$$\frac{\int_0^{N_{\mathrm{S}}^{\mathrm{UL}}}\mathcal{L}_{\max}dN_{\mathrm{S}}}{\int_0^{\infty}\mathcal{L}_{\max}dN_{\mathrm{S}}}=0.90, \tag{2}$$

where $\mathcal{L}_{\max}$ is the value of the likelihood as a function of N_{S}. We find $N_{\mathrm{S}}^{\mathrm{UL}}=6.3$ events.

Figures 2(a)–2(c) show projections of the fit result (solid line) superimposed on the data (points with errors) after further requirements on the discriminating variables to reduce the background level. We consider the three-dimensional signal region defined by $(m_{\mathrm{ES}}>5.27\,\mathrm{GeV}/c^2,|\Delta E|<60\,\mathrm{MeV},\mathcal{F}<1.0)$, and plot a given variable after applying the more restrictive selection on the other two variables. For reference, we also include the expected signal contribution (dashed line) for an assumed branching fraction of 1×10^{-6} (31.5 events). The data are consistent with the background PDF shapes determined from the sideband samples.

As a cross-check on the fit, we apply more stringent background-rejection criteria and determine the signal yield from the observed number of events in a restricted signal region in m_{ES} and ΔE. We require $|\cos\theta_{\mathrm{S}}|<0.7$, and define the signal region as $|\Delta E|<30\,\mathrm{MeV}$ and $5.27<m_{\mathrm{ES}}<5.29\,\mathrm{GeV}/c^2$. Figure 2(d) shows the m_{ES} distribution for events passing the $\cos\theta_{\mathrm{S}}$ and ΔE selection criteria. There are 9 events in the signal region with an expected background of 7.7 ± 1.4, determined by extrapolating the observed yield in the sideband region $5.2<m_{\mathrm{ES}}<5.26\,\mathrm{GeV}/c^2$. The signal yield is 1.3 ± 3.3, which is consistent with the null result from the likelihood fit.

Tables I and II summarize the various sources of systematic error on the signal yield and efficiency. Systematic uncertainty on N_{S} may arise from imperfect knowledge of the PDF parameters. We vary each parameter by its estimated error and combine in quadrature the resulting variations in N_{S}. For the efficiency of the proton selection, we assign the 1.5% background fraction in the Λ control sample as the correlated systematic error. The efficiency of the vertex quality requirement is determined to be 97.5% from simulated $p\overline{p}$ decays, and we assign a systematic uncertainty of 2.5% to account for possible differences between data and Monte Carlo events. As a cross-check, we compare the efficiency in the topologically similar decays $B^0\to\pi^+\pi^-$ and $B^0\to K^+\pi^-$ and find good agreement between data and simulation. Finally, we include a correlated systematic error of 0.8% per track to account for possible differences in tracking efficiency between data and Monte Carlo events. The total systematic uncertainty on the efficiency is computed by adding correlated errors linearly, and then adding the separate sources in quadrature.

We calculate the 90% C.L. upper limit on the branching fraction by increasing $N_{\mathrm{S}}^{\mathrm{UL}}$ by the total systematic error on the signal yield, and by decreasing the efficiency and number of $B\overline{B}$ events by their respective total uncertainties. We find the flavor-averaged branching fraction $\mathcal{B}(B^0\to p\overline{p})<2.7\times10^{-7}$ at the 90% C.L. This result improves the previous limit [3] by more than a factor of 4.

In summary, we have performed a search for the decay $B^0\to p\overline{p}$ in a sample of 88 million $B\overline{B}$ events. We find no evidence for a signal and set an upper limit on the branching fraction at 2.7×10^{-7}. This result rules out the calculation in [5] based on QCD sum rules, while it is consistent with a recent calculation using the pole model [6], and with simple scaling of the measured branching fraction for the decay $B^0\to\Lambda_c^-p$.

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TABLE II. Summary of relative statistical and systematic uncertainties on the signal efficiency. The total uncertainty is the sum in quadrature of the individual contributions.

Source	Uncertainty (%)
Statistical	7.7
Tracking	1.6
Vertex quality	2.5
Proton selection	3.0
DIRC acceptance	1.0
$\cos\theta_{\mathrm{S}}$	5.0
Total	10.2

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[1] Unless otherwise noted, the charge-conjugate mode is implied throughout this paper, and the term ‘‘proton’’ refers to both protons and antiprotons.

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