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Authors
Aubert, B
Barate, R
Boutigny, D
et al.

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Search for a charged partner of the $X(3872)$ in the B meson decay $B \to X^- K$, $X^- \to J/\psi\pi^-\pi^0$

B. Aubert,[1] R. Barate,[1] D. Boutigny,[1] F. Couderc,[1] Y. Karyotakis,[1] J. P. Lees,[1] V. Poireau,[1] V. Tisserand,[1] A. Zghiche,[1] E. Grauges-Pous,[2] A. Palano,[3] A. Pompili,[3] J. C. Chen,[4] N. D. Qi,[4] G. Rong,[4] P. Wang,[4] Y. S. Zhu,[4] G. Eigen,[5] I. Ofte,[5] B. Stugu,[5] G. S. Abrams,[6] A. W. Borgland,[6] A. B. Breon,[6] D. N. Brown,[6] J. Button-Shafer,[6] R. N. Cahn,[6] E. Charles,[6] C. T. Day,[6] M. S. Gill,[6] A. V. Gritsan,[6] Y. Groysman,[6] R. G. Jacobsen,[6] R. W. Kadel,[6] J. Kadyk,[6] L. T. Kerth,[6] Yu. G. Kolomensky,[6] G. Kukartsev,[6] G. Lynch,[6] L. M. Mir,[6] P. J. Oddone,[6] T. J. Orimoto,[6] M. Pripstein,[6] N. A. Roe,[6] M. T. Ronan,[6] W. A. Wenzel,[6] M. Barrett,[7] K. E. Ford,[7] T. J. Harrison,[7] A. J. Hart,[7] C. M. Hawkes,[7] S. E. Morgan,[7] A. T. Watson,[7] M. Fritsch,[8] K. Goetzen,[8] T. Held,[8] H. Koch,[8] B. Lewandowski,[8] M. Pelizaeus,[8] T. Schroeder,[8] M. Steinke,[8] J. T. Boyd,[9] N. Chevalier,[9] W. N. Cottingham,[9] M. P. Kelly,[9] T. E. Latham,[9] F. F. Wilson,[9] T. Cuhadar-Donszelmann,[10] C. Hearty,[10] N. S. Knecht,[10] T. S. Mattison,[10] J. A. McKenna,[10] D. Thiessen,[10] A. Khan,[11] P. Kyberd,[11] L. Teodorescu,[11] A. E. Blinov,[12] V. E. Blinov,[12] V. P. Druzhinin,[12] V. B. Golubev,[12] V. N. Ivanchenko,[12] E. A. Kravchenko,[12] A. P. Onuchin,[12] S. I. Serednyakov,[12] Yu. I. Skovpen,[12] E. P. Solodov,[12] A. N. Yushkov,[12] D. Best,[13] M. Bruinsma,[13] M. Chao,[13] I. Eschrich,[13] D. Kirkby,[13] A. J. Lankford,[13] M. Mandelkern,[13] R. K. Mommsen,[13] W. Roethel,[13] D. P. Stoker,[13] C. Buchanan,[14] B. L. Hartfiel,[14] A. J. R. Weinstein,[14] S. D. Foulkes,[15] J. W. Gary,[15] O. Long,[15] B. C. Shen,[15] K. Wang,[15] D. del Re,[16] H. K. Hadavand,[16] E. J. Hill,[16] D. B. MacFarlane,[16] H. P. Paar,[16] Sh. Rahatlou,[16] V. Sharma,[16] J. Adam Cunha,[17] J. W. Berryhill,[17] C. Campagnari,[17] B. Dahmes,[17] T. M. Hong,[17] A. Lu,[17] M. A. Mazur,[17] J. D. Richman,[17] W. Verkerke,[17] T. W. Beck,[18] A. M. Eisner,[18] C. A. Heusch,[18] J. Kroseberg,[18] W. S. Lockman,[18] G. Nesom,[18] T. Schalk,[18] B. A. Schumm,[18] A. Seiden,[18] P. Spradlin,[18] D. C. Williams,[18] M. G. Wilson,[18] J. Albert,[19] E. Chen,[19] G. P. Dubois-Felsmann,[19] A. Dvoretskii,[19] D. G. Hitlin,[19] I. Narsky,[19] T. Piatenko,[19] F. C. Porter,[19] A. Ryd,[19] A. Samuel,[19] S. Yang,[19] S. Jayatilleke,[20] G. Mancinelli,[20] B. T. Meadows,[20] M. D. Sokoloff,[20] F. Blanc,[21] P. Bloom,[21] S. Chen,[21] W. T. Ford,[21] U. Nauenberg,[21] A. Olivas,[21] P. Rankin,[21] W. O. Ruddick,[21] J. G. Smith,[21] K. A. Ulmer,[21] J. Zhang,[21] L. Zhang,[21] A. Chen,[22] E. A. Eckhart,[22] J. L. Harton,[22] A. Soffer,[22] W. H. Toki,[22] R. J. Wilson,[22] F. Winklmeier,[22] Q. Zeng,[22] B. Spaan,[23] D. Altenburg,[24] T. Brandt,[24] J. Brose,[24] M. Dickopp,[24] E. Feltresi,[24] A. Hauke,[24] H. M. Lacker,[24] R. Nogowski,[24] S. Otto,[24] A. Petzold,[24] J. Schubert,[24] K. R. Schubert,[24] R. Schwierz,[24] J. E. Sundermann,[24] D. Bernard,[25] G. R. Bonneaud,[25] P. Grenier,[25] S. Schrenk,[25] Ch. Thiebaux,[25] G. Vasileiadis,[25] M. Verderi,[25] D. J. Bard,[26] P. J. Clark,[26] F. Muheim,[26] S. Playfer,[26] Y. Xie,[26] M. Andreotti,[27] V. Azzolini,[27] D. Bettoni,[27] C. Bozzi,[27] R. Calabrese,[27] G. Cibinetto,[27] E. Luppi,[27] M. Negrini,[27] L. Piemontese,[27] A. Sarti,[27] E. Treadwell,[28] F. Anulli,[29] R. Baldini-Ferroli,[29] A. Calcaterra,[29] R. de Sangro,[29] G. Finocchiaro,[29] P. Patteri,[29] I. M. Peruzzi,[29] M. Piccolo,[29] A. Zallo,[29] A. Buzzo,[30] R. Capra,[30] R. Contri,[30] G. Crosetti,[30] M. Lo Vetere,[30] M. Macri,[30] M. R. Monge,[30] S. Passaggio,[30] C. Patrignani,[30] E. Robutti,[30] A. Santroni,[30] S. Tosi,[30] S. Bailey,[31] G. Brandenburg,[31] K. S. Chaisanguanthum,[31] M. Morii,[31] E. Won,[31] R. S. Dubitzky,[32] U. Langenegger,[32] J. Marks,[32] U. Uwer,[32] W. Bhimji,[33] D. A. Bowerman,[33] P. D. Dauncey,[33] U. Egede,[33] J. R. Gaillard,[33] G. W. Morton,[33] J. A. Nash,[33] M. B. Nikolich,[33] G. P. Taylor,[33] M. J. Charles,[34] G. J. Grenier,[34] U. Mallik,[34] J. Cochran,[35] H. B. Crawley,[35] J. Lamsa,[35] W. T. Meyer,[35] S. Prell,[35] E. I. Rosenberg,[35] A. E. Rubin,[35] J. Yi,[35] M. Biasini,[36] R. Covarelli,[36] M. Pioppi,[36] N. Arnaud,[37] M. Davier,[37] X. Giroux,[37] G. Grosdidier,[37] A. Höcker,[37] F. Le Diberder,[37] V. Lepeltier,[37] A. M. Lutz,[37] T. C. Petersen,[37] S. Plaszczynski,[37] M. H. Schune,[37] G. Wormser,[37] C. H. Cheng,[38] D. J. Lange,[38] M. C. Simani,[38] D. M. Wright,[38] A. J. Bevan,[39] C. A. Chavez,[39] J. P. Coleman,[39] I. J. Forster,[39] J. R. Fry,[39] E. Gabathuler,[39] R. Gamet,[39] D. E. Hutchcroft,[39] R. J. Parry,[39] D. J. Payne,[39] C. Touramanis,[39] C. M. Cormack,[40] F. Di Lodovico,[40] C. L. Brown,[41] G. Cowan,[41] R. L. Flack,[41] H. U. Flaecher,[41] M. G. Green,[41] P. S. Jackson,[41] T. R. McMahon,[41] S. Ricciardi,[41] F. Salvatore,[41] M. A. Winter,[41] D. Brown,[42] C. L. Davis,[42] J. Allison,[43] N. R. Barlow,[43] R. J. Barlow,[43] M. C. Hodgkinson,[43] G. D. Lafferty,[43] J. C. Williams,[43] C. Chen,[44] A. Farbin,[44] W. D. Hulsbergen,[44] A. Jawahery,[44] D. Kovalskyi,[44] C. K. Lae,[44] V. Lillard,[44] D. A. Roberts,[44] G. Blaylock,[45] C. Dallapiccola,[45] S. S. Hertzbach,[45] R. Kofler,[45] V. B. Koptchev,[45] T. B. Moore,[45] S. Saremi,[45] H. Staengle,[45] S. Willocq,[45] R. Cowan,[46] K. Koeneke,[46] G. Sciolla,[46] S. J. Sekula,[46] F. Taylor,[46] R. K. Yamamoto,[46] P. M. Patel,[47] S. H. Robertson,[47] A. Lazzaro,[48] V. Lombardo,[48] F. Palombo,[48] J. M. Bauer,[49] L. Cremaldi,[49] V. Eschenburg,[49] R. Godang,[49] R. Kroeger,[49] J. Reidy,[49] D. A. Sanders,[49] D. J. Summers,[49] H. W. Zhao,[49] S. Brunet,[50] D. Côté,[50] P. Taras,[50] H. Nicholson,[51] N. Cavallo,[52,*] F. Fabozzi,[52,*] C. Gatto,[52] L. Lista,[52] D. Monorchio,[52] P. Paolucci,[52] D. Piccolo,[52] C. Sciacca,[52] M. Baak,[53] H. Bulten,[53] G. Raven,[53] H. L. Snoek,[53] L. Wilden,[53] C. P. Jessop,[54] J. M. LoSecco,[54] T. Allmendinger,[55] G. Benelli,[55] K. K. Gan,[55] K. Honscheid,[55] D. Hufnagel,[55] H. Kagan,[55] R. Kass,[55] T. Pulliam,[55] A. M. Rahimi,[55] R. Ter-Antonyan,[55] Q. K. Wong,[55] J. Brau,[56] R. Frey,[56] O. Igonkina,[56] M. Lu,[56] C. T. Potter,[56] N. B. Sinev,[56] D. Strom,[56] E. Torrence,[56] F. Colecchia,[57] A. Dorigo,[57] F. Galeazzi,[57] M. Margoni,[57]

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M. Morandin,[57] M. Posocco,[57] M. Rotondo,[57] F. Simonetto,[57] R. Stroili,[57] C. Voci,[57] M. Benayoun,[58] H. Briand,[58] J. Chauveau,[58] P. David,[58] Ch. de la Vaissière,[58] L. Del Buono,[58] O. Hamon,[58] M. J. J. John,[58] Ph. Leruste,[58] J. Malcles,[58] J. Ocariz,[58] L. Roos,[58] G. Therin,[58] P. K. Behera,[59] L. Gladney,[59] Q. H. Guo,[59] J. Panetta,[59] C. Angelini,[60] G. Batignani,[60] S. Bettarini,[60] M. Bondioli,[60] F. Bucci,[60] G. Calderini,[60] M. Carpinelli,[60] F. Forti,[60] M. A. Giorgi,[60] A. Lusiani,[60] G. Marchiori,[60] M. Morganti,[60] N. Neri,[60] E. Paoloni,[60] M. Rama,[60] G. Rizzo,[60] G. Simi,[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] A. D'Orazio,[63] E. Di Marco,[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. Polci,[63] F. Safai Tehrani,[63] C. Voena,[63] S. Christ,[64] H. Schröder,[64] G. Wagner,[64] R. Waldi,[64] T. Adye,[65] N. De Groot,[65] B. Franek,[65] G. P. Gopal,[65] E. O. Olaiya,[65] R. Aleksan,[66] S. Emery,[66] A. Gaidot,[66] S. F. Ganzhur,[66] P.-F. Giraud,[66] G. Hamel de Monchenault,[66] W. Kozanecki,[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] J. R. Wilson,[67] F. X. Yumiceva,[67] T. Abe,[68] M. Allen,[68] D. Aston,[68] R. Bartoldus,[68] N. Berger,[68] A. M. Boyarski,[68] O. L. Buchmueller,[68] R. Claus,[68] M. R. Convery,[68] M. Cristinziani,[68] G. De Nardo,[68] J. C. Dingfelder,[68] D. Dong,[68] J. Dorfan,[68] D. Dujmic,[68] W. Dunwoodie,[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] B. N. Ratcliff,[68] A. Roodman,[68] A. A. Salnikov,[68] R. H. Schindler,[68] J. Schwiening,[68] A. Snyder,[68] A. Soha,[68] J. Stelzer,[68] J. Strube,[56,68] D. Su,[68] M. K. Sullivan,[68] J. Thompson,[68] J. Va'vra,[68] S. R. Wagner,[68] M. Weaver,[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] S. A. Majewski,[69] B. A. Petersen,[69] C. Roat,[69] M. Ahmed,[70] 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] 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] F. Martinez-Vidal,[2,76] R. S. Panvini,[77] Sw. Banerjee,[78] B. Bhuyan,[78] C. M. Brown,[78] D. Fortin,[78] P. D. Jackson,[78] R. Kowalewski,[78] J. M. Roney,[78] R. J. Sobie,[78] J. J. Back,[79] P. F. Harrison,[79] G. B. Mohanty,[79] H. R. Band,[80] X. Chen,[80] B. Cheng,[80] S. Dasu,[80] M. Datta,[80] A. M. Eichenbaum,[80] K. T. Flood,[80] M. Graham,[80] J. J. Hollar,[80] J. R. Johnson,[80] P. E. Kutter,[80] H. Li,[80] R. Liu,[80] A. Mihalyi,[80] Y. Pan,[80] R. Prepost,[80] P. Tan,[80] J. H. von Wimmersperg-Toeller,[80] J. Wu,[80] S. L. Wu,[80] Z. Yu,[80] M. G. Greene,[81] and H. Neal[81]

(*BaBar* Collaboration)

[1]*Laboratoire de Physique des Particules, F-74941 Annecy-le-Vieux, France*
[2]*Universitad Autonoma de Barcelona, E-08193 Bellaterra, Barcelona, Spain*
[3]*Dipartimento di Fisica and INFN, Università di Bari, I-70126 Bari, Italy*
[4]*Institute of High Energy Physics, Beijing 100039, China*
[5]*Institute of Physics, University of Bergen, N-5007 Bergen, Norway*
[6]*Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA*
[7]*University of Birmingham, Birmingham, B15 2TT, United Kingdom*
[8]*Institut für Experimentalphysik 1, Ruhr Universität Bochum, D-44780 Bochum, Germany*
[9]*University of Bristol, Bristol BS8 1TL, United Kingdom*
[10]*University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1*
[11]*Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom*
[12]*Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia*
[13]*University of California at Irvine, Irvine, California 92697, USA*
[14]*University of California at Los Angeles, Los Angeles, California 90024, USA*
[15]*University of California at Riverside, Riverside, California 92521, USA*
[16]*University of California at San Diego, La Jolla, California 92093, USA*
[17]*University of California at Santa Barbara, Santa Barbara, California 93106, USA*
[18]*Institute for Particle Physics, University of California at Santa Cruz, Santa Cruz, California 95064, USA*
[19]*California Institute of Technology, Pasadena, California 91125, USA*
[20]*University of Cincinnati, Cincinnati, Ohio 45221, USA*
[21]*University of Colorado, Boulder, Colorado 80309, USA*
[22]*Colorado State University, Fort Collins, Colorado 80523, USA*
[23]*Institut fur Physik, Universität Dortmund, D-44221 Dortmund, Germany*

[24]*Institut für Kern-und Teilchenphysik, Technische Universität Dresden, D-01062 Dresden, Germany*
[25]*Ecole Polytechnique, LLR, F-91128 Palaiseau, France*
[26]*University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom*
[27]*Dipartimento di Fisica and INFN, Università di Ferrara, I-44100 Ferrara, Italy*
[28]*Florida A&M University, Tallahassee, Florida 32307, USA*
[29]*Laboratori Nazionali di Frascati dell'INFN, I-00044 Frascati, Italy*
[30]*Dipartimento di Fisica and INFN, Università di Genova, I-16146 Genova, Italy*
[31]*Harvard University, Cambridge, Massachusetts 02138, USA*
[32]*Physikalisches Institut, Universität Heidelberg, Philosophenweg 12, D-69120 Heidelberg, Germany*
[33]*Imperial College London, London, SW7 2AZ, United Kingdom*
[34]*University of Iowa, Iowa City, Iowa 52242, USA*
[35]*Iowa State University, Ames, Iowa 50011-3160, USA*
[36]*Dipartimento di Fisica and INFN, Università di Perugia, I-06100 Perugia, Italy*
[37]*Laboratoire de l'Accélérateur Linéaire, F-91898 Orsay, France*
[38]*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
[39]*University of Liverpool, Liverpool L69 72E, United Kingdom*
[40]*Queen Mary, University of London, E1 4NS, United Kingdom*
[41]*Royal Holloway and Bedford New College, University of London, 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]*Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[47]*McGill University, Montréal, Quebec, Canada H3A 2T8*
[48]*Dipartimento di Fisica and INFN, Università di Milano, I-20133 Milano, Italy*
[49]*University of Mississippi, University, Mississippi 38677, USA*
[50]*Laboratoire René J. A. Lévesque, Université de Montréal, Montréal, Quebec, Canada H3C 3J7*
[51]*Mount Holyoke College, South Hadley, Massachusetts 01075, USA*
[52]*Dipartimento di Scienze Fisiche and INFN, Università di Napoli Federico II, 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]*Dipartimento di Fisica and INFN, Università di Padova, I-35131 Padova, Italy*
[58]*Laboratoire de Physique Nucléaire et de Hautes Energies, Universités Paris VI et VII, F-75252 Paris, France*
[59]*University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA*
[60]*Dipartimento di Fisica, Scuola Normale Superiore and INFN, Università di Pisa, I-56127 Pisa, Italy*
[61]*Prairie View A&M University, Prairie View, Texas 77446, USA*
[62]*Princeton University, Princeton, New Jersey 08544, USA*
[63]*Dipartimento di Fisica and INFN, Università di Roma La Sapienza, 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]*Dipartimento di Fisica Sperimentale and INFN, Università di Torino, I-10125 Torino, Italy*
[75]*Dipartimento di Fisica and INFN, Università di Trieste, I-34127 Trieste, Italy*
[76]*Universitad de Valencia, E-46100 Burjassot, Valencia, Spain*
[77]*Vanderbilt University, Nashville, Tennessee 37235, USA*
[78]*University of Victoria, Victoria, British Columbia, Canada V8W 3P6*
[79]*Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom*
[80]*University of Wisconsin, Madison, Wisconsin 53706, USA*

[*]Also with Università della Basilicata, Potenza, Italy.
[†]Deceased.

[81] Yale University, New Haven, Connecticut 06511, USA
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We search for a charged partner of the $X(3872)$ in the decay $B \to X^- K$, $X^- \to J/\psi \pi^- \pi^0$, using 234×10^6 $B\overline{B}$ events collected at the $\Upsilon(4S)$ resonance with the *BABAR* detector at the PEP-II e^+e^- asymmetric-energy storage ring. The resulting product branching fraction upper limits are $\mathcal{B}(B^0 \to X^- K^+, X^- \to J/\psi \pi^- \pi^0) < 5.4 \times 10^{-6}$ and $\mathcal{B}(B^- \to X^- \overline{K}^0, X^- \to J/\psi \pi^- \pi^0) < 22 \times 10^{-6}$ at the 90% confidence level.

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The discovery of the $X(3872)$ by the Belle Collaboration [1] has been confirmed by the CDF [2], D0 [3], and *BABAR* [4] collaborations. Numerous theoretical explanations have been proposed for this high-mass, narrow-width state decaying into $J/\psi \pi^+ \pi^-$. The possibilities [5] include a bound state of $D^* \overline{D}$ very close the $D^{*0}\overline{D}^0$ threshold [6], a hybrid charmonium state [7], a diquark-antidiquark state [8], and a conventional charmonium state [9].

In the Cornell potential model [10], the most likely candidate is a $^3D_2$ ($J^{PC} = 2^{--}$) charmonium state with a 3.830 GeV$/c^2$ mass. This state is expected to be very narrow since the decay to $D\overline{D}$ is forbidden by parity and could decay into an isoscalar $J/\psi \pi^+ \pi^-$ final state. This charmonium state, however, should also have a significant branching ratio for the radiative decay to $\gamma \chi_{c1}$ [10], which was not observed for the $X(3872)$ by Belle [1]. A more detailed examination of the $X(3872)$ observed by Belle [1] and *BABAR* [4] indicates that the $\pi^+ \pi^-$ mass distributions peak near the kinematic upper limit and are consistent with the decay $\rho^0 \to \pi^+ \pi^-$. However, due to limited statistics a spin-parity analysis has not been performed. If the observed decay is $X(3872) \to J/\psi \rho^0$, it cannot be a charmonium state. If the $X(3872)$ and its decays respect isospin symmetry, there must be a $X(3872)^-$, which decays to $J/\psi \rho^-$, and the rate for $B \to X^- K$ should be twice that for $B \to X^0 K$. This would make experimental detection of the X^- quite favorable. To test this hypothesis, we have performed a search for the B-meson decays, $B^0 \to X^- K^+$ and $B^- \to X^- K^0_S$, where $X^- \to J/\psi \pi^- \pi^0$ [11].

Data were collected at the PEP-II asymmetric-energy e^+e^- storage ring with the *BABAR* detector, which is described in detail elsewhere [12]. The data used in this analysis correspond to a total integrated luminosity of 212 fb^{-1} taken on the $\Upsilon(4S)$ resonance, producing a sample of $234.4 \pm 2.6 \times 10^6$ $B\overline{B}$ events ($N_{B\overline{B}}$). The *BABAR* detector uses a silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH), both in a 1.5-T solenoidal magnetic field to detect charged particles and measure their momenta and energy loss (dE/dx). Photons, electrons, and neutral hadrons are detected in a CsI(Tl)-crystal electromagnetic calorimeter (EMC). An internally reflecting ring-imaging Cherenkov detector (DIRC) provides particle-identification information that is complementary to that from dE/dx. Penetrating muons and neutral hadrons are identified by resistive-plate chambers in the steel flux return (IFR). Track-selection criteria in this analysis follow previous *BABAR* analyses [13].

This analysis commences with charged and neutral candidate selections. Each charged-track candidate is required to be detected in at least 12 DCH layers and to have a transverse momentum greater than 100 MeV$/c$. If it is not associated with a K^0_S decay, the candidate must extrapolate to a point near the collision axis.

A charged kaon or pion candidate is selected on the basis of dE/dx information from the SVT and DCH, and the Cherenkov angle measured by the DIRC. An electron candidate is required to have a good match between the expected and measured dE/dx in the DCH, and the Cherenkov angle in the DIRC. The ratio of the shower energy measured in the EMC to the momentum measured in the DCH, and the number of EMC crystals associated with the track candidate, must be appropriate for an electron. A muon is selected on the basis of energy deposited in the EMC, the number and distribution of hits in the IFR, and the match between the IFR hits and the extrapolation of the DCH track into the IFR. A more detailed explanation of particle-identification (PID) is given elsewhere [13,14].

A photon candidate is identified from energy deposited in contiguous EMC crystals, summed to form a cluster that has total energy greater than 30 MeV and a shower shape consistent with that expected for an electromagnetic shower.

The decay modes we use to identify $B^0 \to J/\psi \pi^- \pi^0 K^+$ and $B^- \to J/\psi \pi^- \pi^0 K^0_S$ are $J/\psi \to e^+e^-$, $J/\psi \to \mu^+\mu^-$, $\pi^0 \to \gamma\gamma$, and $K^0_S \to \pi^+\pi^-$. They are selected to be within the mass intervals $2.95 < m(e^+e^-) < 3.14$ GeV$/c^2$, $3.06 < m(\mu^+\mu^-) < 3.14$ GeV$/c^2$, $0.119 < m(\gamma\gamma) < 0.151$ GeV$/c^2$, and $0.4917 < m(\pi^+\pi^-) < 0.5037$ GeV$/c^2$. We take a larger mass interval for e^+e^- than for $\mu^+\mu^-$ to accept events in which part of the energy is carried away by bremsstrahlung photons. The orientation of the displacement vector between the K^0_S decay vertex and the J/ψ vertex in the lab frame is required to be consistent with the K^0_S momentum direction.

The search for B signal events utilizes two kinematic variables: the energy difference ΔE between the energy of the B candidate and the beam-energy $E^*_{\rm b}$ in the $\Upsilon(4S)$ rest frame, and the beam-energy-substituted mass $m_{\rm ES} \equiv \sqrt{(E^*_{\rm b})^2 - (p^*_{\rm B})^2}$, where $p^*_{\rm B}$ is the reconstructed momentum of the B candidate in the $\Upsilon(4S)$ frame. Signal events should have $m_{\mathrm{ES}} \approx m_B$, where m_B is the mass of the B-meson [15], and $|\Delta E| \approx 0$.

Before the data were analyzed, the selection criteria were optimized and fixed separately for the charged and neutral B mode using a Monte Carlo (MC) simulation of signal and known backgrounds. The number of reconstructed MC signal events $n_{\mathrm{s}}^{\mathrm{mc}}$ and the number of reconstructed MC background events $n_{\mathrm{b}}^{\mathrm{mc}}$ (scaled to the integrated luminosity) were used to estimate the sensitivity ratio $n_{\mathrm{s}}^{\mathrm{mc}}/(a/2 + \sqrt{n_{\mathrm{b}}^{\mathrm{mc}}})$ [16], where a, the number of standard deviations of significance desired, was set to 3. Note that the maximum of this ratio is independent of the unknown signal branching fraction. This ratio was maximized by varying the selection criteria on ΔE, m_{ES}, the $X^- \to J/\psi\pi^-\pi^0$ mass, the $K_S^0(\pi^+\pi^-)$ mass, the K_S^0 decay-length significance, the $\pi^0(\gamma\gamma)$ mass, and the particle-identification criteria for electrons, muons, and charged kaons. The selections $|m_{\mathrm{ES}} - m_B| < 5\ \mathrm{MeV}/c^2$, $|\Delta E| < 20$ MeV (signal-box region), and $|m(J/\psi\pi^-\pi^0) - 3872| < 12\ \mathrm{MeV}/c^2$ were found to be optimal for selecting signal events. When there was more than one candidate per event after applying the optimized cuts (on average there were 1.3 candidates/event), the candidate with the smallest value of $|\Delta E|$ was chosen. The plots that follow include only one candidate per event, except for the plots showing ΔE itself.

The ΔE and m_{ES} distributions for the neutral and charged B modes after we apply all the optimized cuts, except the cut for the variable plotted, are shown in Figs. 1(a)–1(d).

A clear peak is observed at zero in the ΔE distribution and near 5.279 GeV/c^2 in the m_{ES} distribution. The other feature in the ΔE plots is a wide peak near 0.2 GeV which

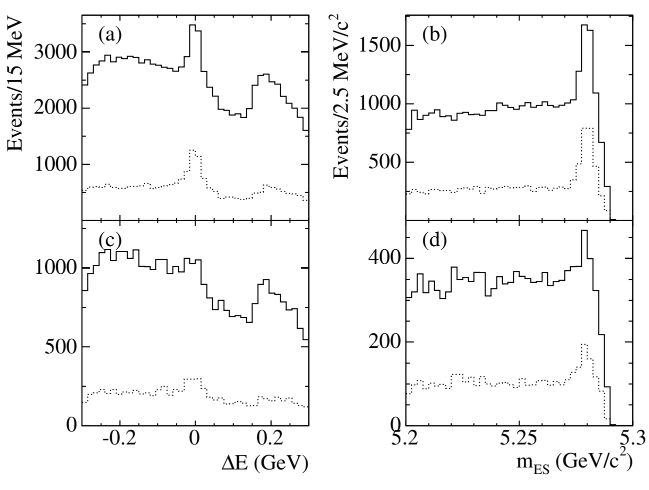

FIG. 1. The ΔE (a) and m_{ES} (b) distributions for the $B^0 \to J/\psi\pi^-\pi^0K^+$ mode and the ΔE (c) and m_{ES} (d) distributions for the $B^- \to J/\psi\pi^-\pi^0K_S^0$ mode using the optimized cuts. The dotted line shows the same with the additional cut $0.67 < m(\pi^-\pi^0) < 0.87\ \mathrm{GeV}/c^2$.

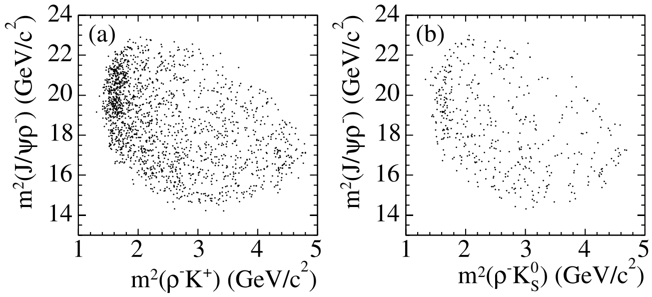

FIG. 2. The $m^2(J/\psi\rho^-)$ versus the $m^2(\rho^-K^+)$ distributions (a) for $B^0 \to J/\psi\pi^-\pi^0K^+$ and the $m^2(J/\psi\rho^-)$ versus the $m^2(\rho^-K_S^0)$ distributions (b) for $B^- \to J/\psi\pi^-\pi^0K_S^0$. A $B \to J/\psi K_1$ signal can be seen; however, there is no indication for an enhancement in the $J/\psi\rho^-$ mass spectrum.

is due to $B \to J/\psi K^*$ decays combined with a random pion.

The Dalitz plots in Fig. 2 for the charged- and neutral-B modes use events in the signal-box region and include a mass cut of $0.67 < m(\pi^-\pi^0) < 0.78\ \mathrm{GeV}/c^2$ to select the ρ^- mass region. There are clear bands for $K_1^0(1270) \to K^+\rho^-$ and $K_1^-(1270) \to K_S^0\rho^-$ corresponding to the decays $B^- \to J/\psi K_1^-$ and $B^0 \to J/\psi K_1^0$ previously observed by Belle [17].

The $J/\psi\pi^-\pi^0$ mass spectra from the neutral and charged B modes are shown in Fig. 3 without a ρ mass cut. No charged signal, $X^- \to J/\psi\pi^-\pi^0$, is evident at $3.872\ \mathrm{GeV}/c^2$.

Extracting an upper limit for $X^- \to J/\psi\pi^-\pi^0$ requires examining the $J/\psi\pi^-\pi^0$ mass, m_{ES}, and ΔE distributions. A signal from $B \to X^-K$, $X^- \to J/\psi\pi^-\pi^0$ should produce signal peaks in all three distributions. Background from $B \to J/\psi\pi^-\pi^0K$ in which the $J/\psi\pi^-\pi^0$ is nonresonant would produce peaks in the m_{ES} and ΔE distributions but have a flat $J/\psi\pi^-\pi^0$ mass distribution near $3.872\ \mathrm{GeV}/c^2$. The combinatoric background will not create peaks in any of the three distributions and should produce an m_{ES} distribution whose shape can be parametrized by an ARGUS function [18]. To estimate the number of signal events (n_S), we count the number of observed events (n_{obs}) in the signal region and subtract the estimated

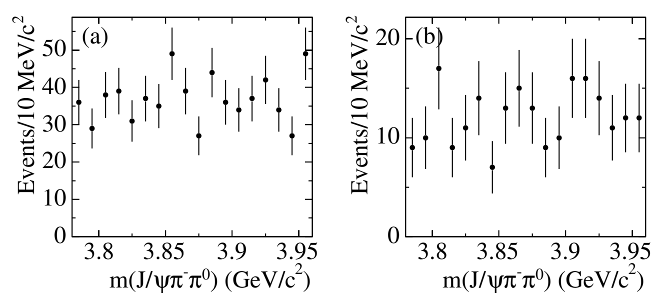

FIG. 3. The $J/\psi\pi^-\pi^0$ invariant mass in 10 MeV/c^2 bins for (a) $B^0 \to J/\psi\pi^-\pi^0K^+$ and (b) for $B^- \to J/\psi\pi^-\pi^0K_S^0$. No indication for the decay $X^- \to J/\psi\pi^-\pi^0$ can be found.

TABLE I. Efficiencies, number of signal-box events, and estimated number of background events n_b ($n_{\rm peak} + n_{\rm comb}$) for the neutral and charged B decays.

Mode	ϵ	$n_{\rm obs}$	$n_{\rm peak} \pm \sigma_{\rm peak}$	$n_{\rm comb} \pm \sigma_{\rm comb}$	$n_b \pm \sigma_b$
B^0	10.65%	96	35.2 ± 8.4	77.6 ± 6.6	112.8 ± 10.7
B^-	8.50%	36	2.0 ± 5.0	29.3 ± 4.1	31.3 ± 6.5

number of combinatoric background events ($n_{\rm comb}$) and the estimated number of peaking background events ($n_{\rm peak}$).

We obtain $n_{\rm obs}$ by counting the number of events satisfying $|m_{\rm ES} - m_B| < 5\ {\rm MeV}/c^2$, $|\Delta E| < 20$ MeV, and $|m(J/\psi\pi^-\pi^0) - 3872| < 12\ {\rm MeV}/c^2$. We extract $n_{\rm comb}$ from the $m_{\rm ES}$ distribution obtained after requiring $|\Delta E| < 20$ MeV, and $|m(J/\psi\pi^-\pi^0) - 3872| < 12\ {\rm MeV}/c^2$. These $m_{\rm ES}$ distributions for the neutral and charged B modes are separately fit with the sum of a signal Gaussian function and an ARGUS function. The resulting ARGUS function is integrated over the $m_{\rm ES}$ range, $|m_{\rm ES} - m_B| < 5\ {\rm MeV}/c^2$, to produce $n_{\rm comb}$. The error $\sigma_{\rm comb}$ is obtained from the fit error on the normalization of the ARGUS function. The resulting values for $n_{\rm comb}$ and $\sigma_{\rm comb}$ are listed in Table I.

We extract $n_{\rm peak}$ from the $m_{\rm ES}$ distribution obtained after requiring $|\Delta E| < 20$ MeV, and $48 < |m(J/\psi\pi^-\pi^0) - 3872| < 72\ {\rm MeV}/c^2$ which is twice the mass range of the signal band. These $m_{\rm ES}$ distributions for the neutral- and charged-B modes are separately fit with the sum of a Gaussian function and an ARGUS function. We calculate $n_{\rm peak}$ by counting the number of events in the $|m_{\rm ES} - m_B| < 5\ {\rm MeV}/c^2$ region, subtracting the number of combinatoric events obtained from integrating the ARGUS function over the same range, $|m_{\rm ES} - m_B| < 5\ {\rm MeV}/c^2$, and finally dividing the result by two. Note that the Gaussian distribution used in all fits has a width fixed to the value determined from a fit to the $m_{\rm ES}$ distribution obtained using both the $J/\psi\pi^-\pi^0$ signal band and the $J/\psi\pi^-\pi^0$ sideband. The error $\sigma_{\rm peak}$ is obtained by adding in quadrature the Poisson errors on the number of events in $|m_{\rm ES} - m_B| < 5\ {\rm MeV}/c^2$ and the fit errors on the normalization of the ARGUS function. The resulting values for $n_{\rm peak}$ and $\sigma_{\rm peak}$ are listed in Table I.

The total background n_b is the sum of the peaking and combinatoric backgrounds and its error σ_b combines in quadrature the errors from the peaking and combinatoric backgrounds. The backgrounds and their errors are summarized in Table I.

The efficiencies ϵ for the processes, $B^0 \to X^- K^+$, $X^- \to J/\psi\pi^-\pi^0$, and $B^- \to X^- K^0_S$, $X^- \to J/\psi\pi^-\pi^0$ are determined by MC simulation with an X^- signal of zero width, mass 3.872 GeV$/c^2$, and a model consisting of the sequential isotropic two-body decays $B \to X^- K$, $X^- \to J/\psi\rho^-$, and $\rho^- \to \pi^-\pi^0$.

These efficiencies are corrected to account for the small differences observed in PID, neutral-particle detection, and tracking efficiency that are found by comparing well-understood control samples taken from data and MC. The final efficiencies for each mode are listed in Table I.

The systematic errors include uncertainties in the number of $B\overline{B}$ events in the data sample, secondary branching fractions, efficiency calculation due to limited MC statistics, decay-model for the generated events, background parametrization, PID, charged particle tracking, and π^0 reconstruction. The individual uncertainties are given as percentages in Table II. The secondary branching fractions [15] include $\mathcal{B}(J/\psi \to e^+e^-, \mu^+\mu^-) = 0.1181 \pm 0.0010$ and $\mathcal{B}(K^0_S \to \pi^+\pi^-) = 0.6895 \pm 0.0014$. The decay-model uncertainty is estimated by comparing the efficiencies for phase space and different decay models [19] with $J^{PC} = 1^{++}$ and $J^{PC} = 2^{--}$ for the X^-.

The background parametrization uncertainty is estimated by varying the background sideband width, refitting the $m_{\rm ES}$ distributions, and recalculating the number of events. The uncertainties in PID, charged-tracking efficiency, and π^0-reconstruction efficiency are determined by studying control samples [13]. The total fractional errors $\sigma_{\rm sys}$, listed at the bottom of Table II, are determined by adding the individual contributions in quadrature.

The probability distribution of the signal events is modeled as a Gaussian with a mean n_s and standard deviation σ_s. For each B-decay mode, the mean is $n_s = n_{\rm obs} - n_b$ and the sigma is $\sigma_s = \sqrt{n_{\rm obs} + \sigma_b^2 + n_s^2\sigma_{\rm sys}^2}$. The systematic error is added in quadrature and scales the errors on $n_{\rm obs}$ and n_b by the same fraction. We note the mean values n_s, for the charged and neutral modes are consistent with zero, within errors.

The number of events N_{90} corresponding to the 90% confidence level (C.L.) upper limit is calculated using the Gaussian probability distribution with the assumption that the number of signal events is always greater than zero. The integral of the distribution from zero to N_{90} will be 90% of the total area above zero. Combining N_{90}, ϵ, $N_{B\overline{B}}$, and the secondary branching fractions, we obtain 90% C.L.

TABLE II. Percentage systematic errors on the branching ratios from the neutral and charged B decay modes.

Systematic errors (%)	B^0	B^-
$N_{B\overline{B}}$	1.1	1.1
Branching fractions	5.3	5.3
MC statistics	2.1	2.3
MC decay-model	1.1	3.0
Background parametrization	0.3	1.7
Particle ID	5.0	5.0
Tracking π^-	1.4	1.4
Tracking K^+	1.4	$\cdots$
Tracking $K^0_S \to \pi^+\pi^-$	$\cdots$	2.6
Tracking $J/\psi \to e^+e^-, \mu^+\mu^-$	1.8	1.8
π^0 reconstruction efficiency	3.2	3.2
TOTAL ($\sigma_{\rm sys}$)	8.8	9.7

TABLE III. The estimated number of signal events, 90% C.L. upper limit of signal events, the branching fraction upper limits, and the branching fraction $\mathcal{B}$ for the decay modes $B^0 \to X^- K^+$ and $B^- \to X^- K^0_S$.

Mode	$n_s \pm \sigma_s$	N_{90}	90% C.L. ($\times 10^{-6}$)	$\mathcal{B}$ ($\times 10^{-6}$)
B^0	-16.8 ± 14.7	15.9	<5.4	-5.7 ± 4.9
B^-	4.7 ± 8.8	17.8	<11	2.0 ± 3.8

upper limits for the neutral and charged B modes of $<5.4 \times 10^{-6}$ and $<11 \times 10^{-6}$, respectively. For completeness we include the central value (68% confidence interval) for the branching fraction using the $n_s \pm \sigma_s$ values. The results are summarized in Table III.

We test the isovector-X hypothesis at a mass of 3872 MeV$/c^2$ using a likelihood ratio test [15]. Here we determine the ratio of the two probabilities from the null (H_0) and signal (H_1) hypotheses using our experimental observation of 96 events in the signal-box.

The null hypothesis assumes the background produced all the observed signal-box events. Assuming the background probability distribution is a Gaussian function with mean n_b and width σ_b, we calculate a probability of $P(H_0) = 5.82 \times 10^{-2}$ to measure 96 or fewer events.

The isovector signal hypothesis predicts the product branching fractions to be related by $\mathcal{B}(B \to X^- K, X^- \to J/\psi\rho^-) = 2 \times \mathcal{B}[B \to X(3872)K, X(3872) \to J/\psi\rho^0]$. Using the *BABAR* branching fraction [4] $\mathcal{B}[B^- \to X(3872)K^-, X(3872) \to J/\psi\pi^+\pi^-] = (1.28 \pm 0.41) \times 10^{-5}$ and assuming all $\pi^+\pi^-$ decays originate from ρ^0, we expect $\mathcal{B}(B^0 \to X^- K^+, X^- \to J/\psi\rho^-) = (2.56 \pm 0.82) \times 10^{-5}$. This would produce 75 ± 25 observed signal events in a data sample of 234×10^6 $B\overline{B}$ events. The error combines the uncertainty on the branching fraction and the systematic error $\sigma_{\rm sys}$ on our efficiency. The probability distributions for the signal events and the estimated background events are modeled as two uncorrelated Gaussian functions. The probability of observing 96 or fewer events (including background) with this probability distribution is $P(H_1) = 8.41 \times 10^{-5}$.

The likelihood ratio (λ) test of the null hypothesis relative to the signal hypothesis yields $\lambda = P(H_0)/P(H_1) = 692$. This corresponds to a probability of less than one part in 600 that the isovector-X hypothesis is compatible with the outcome of our search for $B^0 \to X^- K^+$, $X^- \to J/\psi\pi^-\pi^0$. Performing the same study in our search for $B^- \to X^- K^0_S$, $X^- \to J/\psi\pi^-\pi^0$, we obtain $\lambda = 17$. The combined likelihood ratio is 1.1×10^4. Our result does not support the hypothesis that the $X(3872)$ is an isovector particle decaying to $J/\psi\rho$.

In conclusion, we have performed a search for a charged partner of the $X(3872)$ decaying to $J/\psi\pi^-\pi^0$. Our results set upper limits on the product branching fractions of $\mathcal{B}(B^0 \to X^- K^+, X^- \to J/\psi\pi^-\pi^0) < 5.4 \times 10^{-6}$ and $\mathcal{B}(B^- \to X^- \overline{K}^0, X^- \to J/\psi\pi^-\pi^0) = 2 \times \mathcal{B}(B^- \to X^- K^0_S, X^- \to J/\psi\pi^-\pi^0) < 22 \times 10^{-6}$ at the 90% confidence level.

We exclude the isovector-X hypothesis with a likelihood ratio test which favors the null hypothesis by a factor 1.1×10^4 over the isovector signal hypothesis.

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