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Measurement of Semileptonic B Decays into Orbitally-Excited Charmed Mesons

B. Aubert,[1] M. Bona,[1] Y. Karyotakis,[1] J. P. Lees,[1] V. Poireau,[1] E. Prencipe,[1] X. Prudent,[1] V. Tisserand,[1] J. Garra Tico,[2] E. Grauges,[2] L. Lopez[ab],[3] A. Palano[ab],[3] M. Pappagallo[ab],[3] G. Eigen,[4] B. Stugu,[4] L. Sun,[4] G. S. Abrams,[5] M. Battaglia,[5] D. N. Brown,[5] R. N. Cahn,[5] R. G. Jacobsen,[5] L. T. Kerth,[5] Yu. G. Kolomensky,[5] G. Lynch,[5] I. L. Osipenkov,[5] M. T. Ronan,[5, *] K. Tackmann,[5] T. Tanabe,[5] C. M. Hawkes,[6] N. Soni,[6] A. T. Watson,[6] H. Koch,[7] T. Schroeder,[7] D. Walker,[8] D. J. Asgeirsson,[9] B. G. Fulsom,[9] C. Hearty,[9] T. S. Mattison,[9] J. A. McKenna,[9] M. Barrett,[10] A. Khan,[10] V. E. Blinov,[11] A. D. Bukin,[11] A. R. Buzykaev,[11] V. P. Druzhinin,[11] V. B. Golubev,[11] A. P. Onuchin,[11] S. I. Serednyakov,[11] Yu. I. Skovpen,[11] E. P. Solodov,[11] K. Yu. Todyshev,[11] M. Bondioli,[12] S. Curry,[12] I. Eschrich,[12] D. Kirkby,[12] A. J. Lankford,[12] P. Lund,[12] M. Mandelkern,[12] E. C. Martin,[12] D. P. Stoker,[12] S. Abachi,[13] C. Buchanan,[13] J. W. Gary,[14] F. Liu,[14] O. Long,[14] B. C. Shen,[14, *] G. M. Vitug,[14] Z. Yasin,[14] L. Zhang,[14] V. Sharma,[15] C. Campagnari,[16] T. M. Hong,[16] D. Kovalskyi,[16] M. A. Mazur,[16] J. D. Richman,[16] T. W. Beck,[17] A. M. Eisner,[17] C. J. Flacco,[17] C. A. Heusch,[17] J. Kroseberg,[17] W. S. Lockman,[17] A. J. Martinez,[17] T. Schalk,[17] B. A. Schumm,[17] A. Seiden,[17] M. G. Wilson,[17] L. O. Winstrom,[17] C. H. Cheng,[18] D. A. Doll,[18] B. Echenard,[18] F. Fang,[18] D. G. Hitlin,[18] I. Narsky,[18] T. Piatenko,[18] F. C. Porter,[18] R. Andreassen,[19] G. Mancinelli,[19] B. T. Meadows,[19] K. Mishra,[19] M. D. Sokoloff,[19] P. C. Bloom,[20] W. T. Ford,[20] A. Gaz,[20] J. F. Hirschauer,[20] M. Nagel,[20] U. Nauenberg,[20] J. G. Smith,[20] K. A. Ulmer,[20] S. R. Wagner,[20] R. Ayad,[21, †] A. Soffer,[21, ‡] W. H. Toki,[21] R. J. Wilson,[21] D. D. Altenburg,[22] E. Feltresi,[22] A. Hauke,[22] H. Jasper,[22] M. Karbach,[22] J. Merkel,[22] A. Petzold,[22] B. Spaan,[22] K. Wacker,[22] M. J. Kobel,[23] W. F. Mader,[23] R. Nogowski,[23] K. R. Schubert,[23] R. Schwierz,[23] A. Volk,[23] D. Bernard,[24] G. R. Bonneaud,[24] E. Latour,[24] M. Verderi,[24] P. J. Clark,[25] S. Playfer,[25] J. E. Watson,[25] M. Andreotti[ab],[26] D. Bettoni[a],[26] C. Bozzi[a],[26] R. Calabrese[ab],[26] A. Cecchi[ab],[26] G. Cibinetto[ab],[26] P. Franchini[ab],[26] E. Luppi[ab],[26] M. Negrini[ab],[26] A. Petrella[ab],[26] L. Piemontese[a],[26] V. Santoro[ab],[26] R. Baldini-Ferroli,[27] A. Calcaterra,[27] R. de Sangro,[27] G. Finocchiaro,[27] S. Pacetti,[27] P. Patteri,[27] I. M. Peruzzi,[27, §] M. Piccolo,[27] M. Rama,[27] A. Zallo,[27] A. Buzzo[a],[28] R. Contri[ab],[28] M. Lo Vetere[ab],[28] M. M. Macri[a],[28] M. R. Monge[ab],[28] S. Passaggio[a],[28] C. Patrignani[ab],[28] E. Robutti[a],[28] A. Santroni[ab],[28] S. Tosi[ab],[28] K. S. Chaisanguanthum,[29] M. Morii,[29] A. Adametz,[30] J. Marks,[30] S. Schenk,[30] U. Uwer,[30] V. Klose,[31] H. M. Lacker,[31] D. J. Bard,[32] P. D. Dauncey,[32] J. A. Nash,[32] M. Tibbetts,[32] P. K. Behera,[33] X. Chai,[33] M. J. Charles,[33] U. Mallik,[33] J. Cochran,[34] H. B. Crawley,[34] L. Dong,[34] W. T. Meyer,[34] S. Prell,[34] E. I. Rosenberg,[34] A. E. Rubin,[34] Y. Y. Gao,[35] A. V. Gritsan,[35] Z. J. Guo,[35] C. K. Lae,[35] N. Arnaud,[36] J. Béquilleux,[36] A. D'Orazio,[36] M. Davier,[36] J. Firmino da Costa,[36] G. Grosdidier,[36] A. Höcker,[36] V. Lepeltier,[36] F. Le Diberder,[36] A. M. Lutz,[36] S. Pruvot,[36] P. Roudeau,[36] M. H. Schune,[36] J. Serrano,[36] V. Sordini,[36, ¶] A. Stocchi,[36] G. Wormser,[36] D. J. Lange,[37] D. M. Wright,[37] I. Bingham,[38] J. P. Burke,[38] C. A. Chavez,[38] J. R. Fry,[38] E. Gabathuler,[38] R. Gamet,[38] D. E. Hutchcroft,[38] D. J. Payne,[38] C. Touramanis,[38] A. J. Bevan,[39] C. K. Clarke,[39] K. A. George,[39] F. Di Lodovico,[39] R. Sacco,[39] M. Sigamani,[39] G. Cowan,[40] H. U. Flaecher,[40] D. A. Hopkins,[40] S. Paramesvaran,[40] F. Salvatore,[40] A. C. Wren,[40] D. N. Brown,[41] C. L. Davis,[41] A. G. Denig,[42] M. Fritsch,[42] W. Gradl,[42] G. Schott,[42] K. E. Alwyn,[43] D. Bailey,[43] R. J. Barlow,[43] Y. M. Chia,[43] C. L. Edgar,[43] G. Jackson,[43] G. D. Lafferty,[43] T. J. West,[43] J. I. Yi,[43] J. Anderson,[44] C. Chen,[44] A. Jawahery,[44] D. A. Roberts,[44] G. Simi,[44] J. M. Tuggle,[44] C. Dallapiccola,[45] X. Li,[45] E. Salvati,[45] S. Saremi,[45] R. Cowan,[46] D. Dujmic,[46] P. H. Fisher,[46] G. Sciolla,[46] M. Spitznagel,[46] F. Taylor,[46] R. K. Yamamoto,[46] M. Zhao,[46] P. M. Patel,[47] S. H. Robertson,[47] A. Lazzaro[ab],[48] V. Lombardo[a],[48] F. Palombo[ab],[48] J. M. Bauer,[49] L. Cremaldi,[49] R. Godang,[49, **] R. Kroeger,[49] D. A. Sanders,[49] D. J. Summers,[49] H. W. Zhao,[49] M. Simard,[50] P. Taras,[50] F. B. Viaud,[50] H. Nicholson,[51] G. De Nardo[ab],[52] L. Lista[a],[52] D. Monorchio[ab],[52] G. Onorato[ab],[52] C. Sciacca[ab],[52] G. Raven,[53] H. L. Snoek,[53] C. P. Jessop,[54] K. J. Knoepfel,[54] J. M. LoSecco,[54] W. F. Wang,[54] G. Benelli,[55] L. A. Corwin,[55] K. Honscheid,[55] H. Kagan,[55] R. Kass,[55] J. P. Morris,[55] A. M. Rahimi,[55] J. J. Regensburger,[55] S. J. Sekula,[55] Q. K. Wong,[55] N. L. Blount,[56] J. Brau,[56] R. Frey,[56] O. Igonkina,[56] J. A. Kolb,[56] M. Lu,[56]

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R. Rahmat,[56] N. B. Sinev,[56] D. Strom,[56] J. Strube,[56] E. Torrence,[56] G. Castelli[ab],[57] N. Gagliardi[ab],[57] M. Margoni[ab],[57] M. Morandin[a],[57] M. Posocco[a],[57] M. Rotondo[a],[57] F. Simonetto[ab],[57] R. Stroili[ab],[57] C. Voci[ab],[57] P. del Amo Sanchez,[58] E. Ben-Haim,[58] H. Briand,[58] G. Calderini,[58] J. Chauveau,[58] P. David,[58] L. Del Buono,[58] O. Hamon,[58] Ph. Leruste,[58] J. Ocariz,[58] A. Perez,[58] J. Prendki,[58] S. Sitt,[58] L. Gladney,[59] M. Biasini[ab],[60] R. Covarelli[ab],[60] E. Manoni[ab],[60] C. Angelini[ab],[61] G. Batignani[ab],[61] S. Bettarini[ab],[61] M. Carpinelli[ab],[61, ††] A. Cervelli[ab],[61] F. Forti[ab],[61] M. A. Giorgi[ab],[61] A. Lusiani[ac],[61] G. Marchiori[ab],[61] M. Morganti[ab],[61] N. Neri[ab],[61] E. Paoloni[ab],[61] G. Rizzo[ab],[61] J. J. Walsh[a],[61] D. Lopes Pegna,[62] C. Lu,[62] J. Olsen,[62] A. J. S. Smith,[62] A. V. Telnov,[62] F. Anulli[a],[63] E. Baracchini[ab],[63] G. Cavoto[a],[63] D. del Re[ab],[63] E. Di Marco[ab],[63] R. Faccini[ab],[63] F. Ferrarotto[a],[63] F. Ferroni[ab],[63] M. Gaspero[ab],[63] P. D. Jackson[a],[63] L. Li Gioi[a],[63] M. A. Mazzoni[a],[63] S. Morganti[a],[63] G. Piredda[a],[63] F. Polci[ab],[63] F. Renga[ab],[63] C. Voena[a],[63] M. Ebert,[64] T. Hartmann,[64] H. Schröder,[64] R. Waldi,[64] T. Adye,[65] B. Franek,[65] E. O. Olaiya,[65] F. F. Wilson,[65] S. Emery,[66] M. Escalier,[66] L. Esteve,[66] S. F. Ganzhur,[66] G. Hamel de Monchenault,[66] W. Kozanecki,[66] G. Vasseur,[66] Ch. Yèche,[66] M. Zito,[66] X. R. Chen,[67] H. Liu,[67] W. Park,[67] M. V. Purohit,[67] R. M. White,[67] J. R. Wilson,[67] M. T. Allen,[68] D. Aston,[68] R. Bartoldus,[68] P. Bechtle,[68] J. F. Benitez,[68] R. Cenci,[68] J. P. Coleman,[68] M. R. Convery,[68] J. C. Dingfelder,[68] J. Dorfan,[68] G. P. Dubois-Felsmann,[68] W. Dunwoodie,[68] R. C. Field,[68] A. M. Gabareen,[68] S. J. Gowdy,[68] M. T. Graham,[68] P. Grenier,[68] C. Hast,[68] W. R. Innes,[68] J. Kaminski,[68] M. H. Kelsey,[68] H. Kim,[68] P. Kim,[68] M. L. Kocian,[68] D. W. G. S. Leith,[68] S. Li,[68] B. Lindquist,[68] S. Luitz,[68] V. Luth,[68] H. L. Lynch,[68] D. B. MacFarlane,[68] H. Marsiske,[68] R. Messner,[68] D. R. Muller,[68] H. Neal,[68] S. Nelson,[68] C. P. O'Grady,[68] I. Ofte,[68] A. Perazzo,[68] M. Perl,[68] B. N. Ratcliff,[68] A. Roodman,[68] A. A. Salnikov,[68] R. H. Schindler,[68] J. Schwiening,[68] A. Snyder,[68] D. Su,[68] M. K. Sullivan,[68] K. Suzuki,[68] S. K. Swain,[68] J. M. Thompson,[68] J. Va'vra,[68] A. P. Wagner,[68] M. Weaver,[68] C. A. West,[68] W. J. Wisniewski,[68] M. Wittgen,[68] D. H. Wright,[68] H. W. Wulsin,[68] A. K. Yarritu,[68] K. Yi,[68] C. C. Young,[68] V. Ziegler,[68] P. R. Burchat,[69] A. J. Edwards,[69] S. A. Majewski,[69] T. S. Miyashita,[69] B. A. Petersen,[69] L. Wilden,[69] S. Ahmed,[70] M. S. Alam,[70] J. A. Ernst,[70] B. Pan,[70] M. A. Saeed,[70] S. B. Zain,[70] S. M. Spanier,[71] B. J. Wogsland,[71] R. Eckmann,[72] J. L. Ritchie,[72] A. M. Ruland,[72] C. J. Schilling,[72] R. F. Schwitters,[72] B. W. Drummond,[73] J. M. Izen,[73] X. C. Lou,[73] F. Bianchi[ab],[74] D. Gamba[ab],[74] M. Pelliccioni[ab],[74] M. Bomben[ab],[75] L. Bosisio[ab],[75] C. Cartaro[ab],[75] G. Della Ricca[ab],[75] L. Lanceri[ab],[75] L. Vitale[ab],[75] V. Azzolini,[76] N. Lopez-March,[76] F. Martinez-Vidal,[76] D. A. Milanes,[76] A. Oyanguren,[76] J. Albert,[77] Sw. Banerjee,[77] B. Bhuyan,[77] H. H. F. Choi,[77] K. Hamano,[77] R. Kowalewski,[77] M. J. Lewczuk,[77] I. M. Nugent,[77] J. M. Roney,[77] R. J. Sobie,[77] T. J. Gershon,[78] P. F. Harrison,[78] J. Ilic,[78] T. E. Latham,[78] G. B. Mohanty,[78] H. R. Band,[79] X. Chen,[79] S. Dasu,[79] K. T. Flood,[79] Y. Pan,[79] M. Pierini,[79] R. Prepost,[79] C. O. Vuosalo,[79] and S. L. Wu[79]

(The *BABAR* Collaboration)

[1] *Laboratoire de Physique des Particules, IN2P3/CNRS et Université de Savoie, F-74941 Annecy-Le-Vieux, France*
[2] *Universitat de Barcelona, Facultat de Fisica, Departament ECM, E-08028 Barcelona, Spain*
[3] *INFN Sezione di Bari[a]; Dipartmento di Fisica, Università di Bari[b], I-70126 Bari, Italy*
[4] *University of Bergen, Institute of Physics, N-5007 Bergen, Norway*
[5] *Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA*
[6] *University of Birmingham, Birmingham, B15 2TT, United Kingdom*
[7] *Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany*
[8] *University of Bristol, Bristol BS8 1TL, United Kingdom*
[9] *University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1*
[10] *Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom*
[11] *Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia*
[12] *University of California at Irvine, Irvine, California 92697, USA*
[13] *University of California at Los Angeles, Los Angeles, California 90024, USA*
[14] *University of California at Riverside, Riverside, California 92521, USA*
[15] *University of California at San Diego, La Jolla, California 92093, USA*
[16] *University of California at Santa Barbara, Santa Barbara, California 93106, USA*
[17] *University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA*
[18] *California Institute of Technology, Pasadena, California 91125, USA*
[19] *University of Cincinnati, Cincinnati, Ohio 45221, USA*
[20] *University of Colorado, Boulder, Colorado 80309, USA*
[21] *Colorado State University, Fort Collins, Colorado 80523, USA*
[22] *Technische Universität Dortmund, Fakultät Physik, D-44221 Dortmund, Germany*
[23] *Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany*
[24] *Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, F-91128 Palaiseau, France*
[25] *University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom*

[26]INFN Sezione di Ferrara[a]; Dipartimento di Fisica, Università di Ferrara[b], I-44100 Ferrara, Italy
[27]INFN Laboratori Nazionali di Frascati, I-00044 Frascati, Italy
[28]INFN Sezione di Genova[a]; Dipartimento di Fisica, Università di Genova[b], I-16146 Genova, Italy
[29]Harvard University, Cambridge, Massachusetts 02138, USA
[30]Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany
[31]Humboldt-Universität zu Berlin, Institut für Physik, Newtonstr. 15, D-12489 Berlin, Germany
[32]Imperial College London, London, SW7 2AZ, United Kingdom
[33]University of Iowa, Iowa City, Iowa 52242, USA
[34]Iowa State University, Ames, Iowa 50011-3160, USA
[35]Johns Hopkins University, Baltimore, Maryland 21218, USA
[36]Laboratoire de l'Accélérateur Linéaire, IN2P3/CNRS et Université Paris-Sud 11, Centre Scientifique d'Orsay, B. P. 34, F-91898 Orsay Cedex, France
[37]Lawrence Livermore National Laboratory, Livermore, California 94550, USA
[38]University of Liverpool, Liverpool L69 7ZE, United Kingdom
[39]Queen Mary, University of London, London, E1 4NS, United Kingdom
[40]University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom
[41]University of Louisville, Louisville, Kentucky 40292, USA
[42]Johannes Gutenberg-Universität Mainz, Institut für Kernphysik, D-55099 Mainz, Germany
[43]University of Manchester, Manchester M13 9PL, United Kingdom
[44]University of Maryland, College Park, Maryland 20742, USA
[45]University of Massachusetts, Amherst, Massachusetts 01003, USA
[46]Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA
[47]McGill University, Montréal, Québec, Canada H3A 2T8
[48]INFN Sezione di Milano[a]; Dipartimento di Fisica, Università di Milano[b], I-20133 Milano, Italy
[49]University of Mississippi, University, Mississippi 38677, USA
[50]Université de Montréal, Physique des Particules, Montréal, Québec, Canada H3C 3J7
[51]Mount Holyoke College, South Hadley, Massachusetts 01075, USA
[52]INFN Sezione di Napoli[a]; Dipartimento di Scienze Fisiche, Università di Napoli Federico II[b], I-80126 Napoli, Italy
[53]NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands
[54]University of Notre Dame, Notre Dame, Indiana 46556, USA
[55]Ohio State University, Columbus, Ohio 43210, USA
[56]University of Oregon, Eugene, Oregon 97403, USA
[57]INFN Sezione di Padova[a]; Dipartimento di Fisica, Università di Padova[b], I-35131 Padova, Italy
[58]Laboratoire de Physique Nucléaire et de Hautes Energies, IN2P3/CNRS, Université Pierre et Marie Curie-Paris6, Université Denis Diderot-Paris7, F-75252 Paris, France
[59]University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
[60]INFN Sezione di Perugia[a]; Dipartimento di Fisica, Università di Perugia[b], I-06100 Perugia, Italy
[61]INFN Sezione di Pisa[a]; Dipartimento di Fisica, Università di Pisa[b]; Scuola Normale Superiore di Pisa[c], I-56127 Pisa, Italy
[62]Princeton University, Princeton, New Jersey 08544, USA
[63]INFN Sezione di Roma[a]; Dipartimento di Fisica, Università di Roma La Sapienza[b], I-00185 Roma, Italy
[64]Universität Rostock, D-18051 Rostock, Germany
[65]Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom
[66]CEA, Irfu, SPP, Centre de Saclay, F-91191 Gif-sur-Yvette, France
[67]University of South Carolina, Columbia, South Carolina 29208, USA
[68]Stanford Linear Accelerator Center, Stanford, California 94309, USA
[69]Stanford University, Stanford, California 94305-4060, USA
[70]State University of New York, Albany, New York 12222, USA
[71]University of Tennessee, Knoxville, Tennessee 37996, USA
[72]University of Texas at Austin, Austin, Texas 78712, USA
[73]University of Texas at Dallas, Richardson, Texas 75083, USA
[74]INFN Sezione di Torino[a]; Dipartimento di Fisica Sperimentale, Università di Torino[b], I-10125 Torino, Italy
[75]INFN Sezione di Trieste[a]; Dipartimento di Fisica, Università di Trieste[b], I-34127 Trieste, Italy
[76]IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain
[77]University of Victoria, Victoria, British Columbia, Canada V8W 3P6
[78]Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom
[79]University of Wisconsin, Madison, Wisconsin 53706, USA

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We present a study of B decays into semileptonic final states containing charged and neutral $D_1(2420)$ and $D_2^*(2460)$. The analysis is based on a data sample of $208\,\mathrm{fb}^{-1}$ collected at the $\Upsilon(4S)$

resonance with the *BABAR* detector at the PEP-II asymmetric-energy B Factory at SLAC. With a simultaneous fit to four different decay chains, the semileptonic branching fractions are extracted from measurements of the mass difference $\Delta m = m(D^{**}) - m(D)$ distributions. Product branching fractions are determined to be $\mathcal{B}(B^+ \to D_1^0 \ell^+ \nu_\ell) \times \mathcal{B}(D_1^0 \to D^{*+}\pi^-) = (2.97 \pm 0.17 \pm 0.17) \times 10^{-3}$, $\mathcal{B}(B^+ \to D_2^{*0} \ell^+ \nu_\ell) \times \mathcal{B}(D_2^{*0} \to D^{(*)+}\pi^-) = (2.29 \pm 0.23 \pm 0.21) \times 10^{-3}$, $\mathcal{B}(B^0 \to D_1^- \ell^+ \nu_\ell) \times \mathcal{B}(D_1^- \to D^{*0}\pi^-) = (2.78 \pm 0.24 \pm 0.25) \times 10^{-3}$ and $\mathcal{B}(B^0 \to D_2^{*-} \ell^+ \nu_\ell) \times \mathcal{B}(D_2^{*-} \to D^{(*)0}\pi^-) = (1.77 \pm 0.26 \pm 0.11) \times 10^{-3}$. In addition we measure the branching ratio $\Gamma(D_2^* \to D\pi^-)/\Gamma(D_2^* \to D^{(*)}\pi^-) = 0.62 \pm 0.03 \pm 0.02$.

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Higher excitations than the D^* play an important role in the understanding of semileptonic B decays. Among these are the orbitally excited D^{**} states. Precise knowledge of their properties is important to reduce the uncertainties on measurements of other semileptonic decays, and thus the determination of the CKM elements $|V_{cb}|$ and $|V_{ub}|$. In the framework of Heavy Quark Symmetry, they form two doublets with $j_q^P = 1/2^-$ and $j_q^P = 3/2^-$ where j_q^P denotes the spin-parity of the light quark coupled to the orbital angular momentum. The doublet with $j_q^P = 3/2^-$, namely the D_1 and D_2^*, have to decay via D wave to conserve parity and angular momentum and therefore are narrow with widths of order of 10 MeV [1]. In this paper we describe a simultaneous measurement of all B semileptonic decays to the two narrow orbitally-excited charmed states without explicit reconstruction of the rest of the event.

The CLEO collaboration has previously reported a branching fraction measurement for $B^+ \to D_1^0 \ell^+ \nu$ and an upper limit for $B^+ \to D_2^{*0} \ell^+ \nu$ [2]. More recently Belle and *BABAR* have reported results using a technique in which one of the B mesons in the process $\Upsilon(4S) \to B\overline{B}$ is fully reconstructed [3].

From the complete data set collected with the *BABAR* detector at the PEP-II storage ring, in this analysis we use a sample with a total integrated luminosity of $208\,\text{fb}^{-1}$, which has been recorded at a center of mass energy of 10.58 GeV.

The *BABAR* detector [4] and event reconstruction [5] are described in detail elsewhere. A Monte Carlo (MC) simulation based on GEANT4 [6] is used to estimate signal efficiencies and to understand the backgrounds. The sample of simulated $B\overline{B}$ events is equivalent to approximately three times the data sample. In addition a dedicated simulation of signal events based on the ISGW2 model [7] has been produced with statistics equivalent to roughly five times the expected signal yield contained in the data.

D^{**} decays are reconstructed in the decay chains $D^{**} \to D^*\pi^-$ [8], and $D^{**} \to D\pi^-$. The former is accessible to both narrow D^{**} states while the latter has no contribution from the D_1. Intermediate D^* states are reconstructed in $D^* \to D^0\pi$ and the D mesons are reconstructed exclusively in $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$. D^{**} candidates are then paired with reconstructed leptons and required to be consistent with the semileptonic decays $B \to D^{**}\ell\nu$, as described in the following.

First, events which are most likely to contain a semileptonic B decay are selected. We require that there is a reconstructed D candidate and at least one lepton in the event with a momentum greater than $800\,\text{MeV}/c$ [9]. Neutral D meson candidates are formed by $K^-\pi^+$ combinations requiring the invariant mass to be consistent with the D^0 mass: $1.846 < m(K\pi) < 1.877\,\text{GeV}/c^2$. This asymmetric mass window is chosen to take into account resolution effects of the detector. The selection is optimized to maximize the significance of the selected sample.

D^0 candidates are combined with charged and neutral pions to form D^* candidates. For charged D^* the mass difference between the D^* candidate and the D^0 candidate is required to be $144 < m(D^0\pi^+) - m(D^0) < 148\,\text{MeV}/c^2$. For neutral D^* the π^0 is reconstructed from a photon pair with an invariant mass of $115 < m_{\gamma\gamma} < 150\,\text{MeV}/c^2$. Those photon pairs are re-fitted in a mass constrained fit to match the nominal mass of the π^0. The mass difference between the D^{*0} candidate and the D^0 candidate is required to be $140 < m(D^0\pi^0) - m(D^0) < 144\,\text{MeV}/c^2$.

D^+ candidates are formed from $K^-\pi^+\pi^+$ combinations with an invariant mass of $1.854 < m(K\pi\pi) < 1.884\,\text{GeV}/c^2$. The probability that the three tracks originate from a common vertex, P_{Vtx}, is required to be $P_{\text{Vtx}}(K\pi\pi) > 0.01$.

Candidates for D and D^* are combined with charged pions to form D^{**} candidates. These D^{**} candidates are combined with muons or electrons. The charge of the lepton is required to match the charge of the kaon from the D decay.

Part of the background is due to events where a D^{**} is paired to a lepton from the other B. Thus we require that the probability that the lepton and the pion emitted by the D^{**} originate from a common vertex exceeds 0.001, and that the angle between the direction of flight of the D^{**} and the lepton is more than 90 degrees.

A dominant fraction of the background events is due to $B \to D^*\ell\nu$ decays where the D^* or its daughter D is paired to a pion from the other B. To suppress this combinatorial background we make use of the variable cos_{BY} described in the following. The energy and momentum of the B mesons from the $\Upsilon(4S)$ decays are known from incident beam energies. For correctly reconstructed $B \to D^{**}\ell\nu$ decays, where the only missing particle is the neutrino, the decay kinematics can be calculated, up to one angular quantity, from the four-momentum of the visible decay products ($Y = D^{**}\ell$). The cosine of the angle between the direction of flight of the B meson and its visible decay product Y is given by

$$cos_{BY} = -\frac{2E_B E_Y - m_B^2 - m_Y^2}{2|\vec{p}_B||\vec{p}_Y|}$$

where E, $|\vec{p}|$ and m are the energies, momenta and masses of the B and the Y respectively. If the Y candidate is not from a correctly reconstructed $B \to D^{**}\ell\nu$ decay, the quantity cos_{BY} no longer represents an angle, and can take any value. We therefore select candidates having $|cos_{BY}| \leq 1$.

In case a D^* is reconstructed in the decay chain, a veto is applied against decays $B \to D^*\ell\nu$ by calculating the variable $cos_{BY'}$ which is defined as above but the Y system is redefined to contain only the D^* and the lepton: $Y' = D^*\ell$. In this variable, signal events of the type $B \to D^{**}\ell\nu$ tend to have values less than -1. Background events are rejected by the requirement $cos_{BY'} < -1$.

To reduce combinatorial backgrounds in the decay chain $D^{**}{\to}D\pi^-$, only the $D^{**}\ell$ candidate with $\tilde{m}_\nu^2$ closest to zero is selected, where $\tilde{m}_\nu^2$ is the neutrino mass squared, calculated in the approximation $\vec{p}_B = 0$: $\tilde{m}_\nu^2 = m_B^2 + |\vec{p}_Y|^2 - 2E_B E_Y$. Events reconstructed in the $D^{**}{\to}D^0\pi^-$ final state are rejected if the D^0 can be paired with any charged pion to form a D^{*+} candidate as described above.

In about 2% of the events more than one $D^{**}\ell$ candidate is selected and if so all of them enter the analysis.

We determine the D_2^* signal yield in the $B \to D\pi^-\ell^+\nu$ final states and the D_1 and D_2^* signal yields in the $B \to D^*\pi^-\ell^+\nu$ final state by a binned χ^2 fit to the $\Delta m = m(D^{(*)}\pi^-) - m(D^0)$ distributions. To determine the individual contributions from D_1 and D_2^* in the $B \to D^*\pi^-\ell^+\nu$ final state, we make use of the helicity angle distribution of the D^*, ϑ_h, which is defined as the angle between the two pions emitted by the D^{**} and the D^* in the rest frame of the D^*. For a D^* from a D_2^* this angle varies as $\sin^2\vartheta_h$, whereas for D_1 decays, the helicity angle is distributed like $1 + A_{D_1}\cos^2\vartheta_h$, where A_{D_1} is a parameter which depends on the initial polarization of the D_1 and a possible contribution of the S-wave to the D_1 decay. To exploit this feature, we split the data for the two decay chains involving a D^* into four subsamples, corresponding to four equal size bins in $|\cos\vartheta_h|$.

The resulting ten Δm distributions are fitted simultaneously to determine 12 parameters describing the signal yields and distributions, and 22 parameters to adjust the background yields and shapes. The mass differences for the signal events are described by Breit-Wigner functions. There are four parameters giving the signal yields for the semileptonic decays involving the two narrow states, charged and neutral. The masses of the states are also fitted, but are constrained to be equal for charged and neutral states, giving two parameters. Four additional parameters arise from the effective widths of the D^{**} states, which represent a convolution of the intrinsic widths and detector resolution effects. The detector resolution contributes approximately $2 - 3\,\mathrm{MeV}/c^2$ depending on the mode. The fit also determines the D_2^* branching ratio $\mathcal{B}_{D/D^*} = \Gamma(D_2^* \to D\pi^-)/(\Gamma(D_2^* \to D\pi^-) + \Gamma(D_2^* \to D^*\pi^-))$ and the D_1 polarization amplitude A_{D_1}.

Backgrounds are modeled by cubic functions in Δm. The background shape in the $D^*\pi^-$ channel is found to be the same in all helicity bins for each final state. The fit thus has three shape parameters for each decay chain, while the number of background events is determined independently in each bin.

The selection efficiency is deduced from a fit to the simulation. This fit uses the same parametrization as the fit determining the signal yield from data and is applied to the sum of the full background simulation and for one signal decay chain at a time. For a given decay mode the efficiencies are found to be the same for D_1 and D_2^*, specifically, $\epsilon(D^{*+}\pi^-) = (6.89 \pm 0.12)\%$, $\epsilon(D^{*0}\pi^-) = (5.34 \pm 0.12)\%$, $\epsilon(D^+\pi^-) = (12.88 \pm 0.96)\%$ and $\epsilon(D^0\pi^-) = (17.56 \pm 0.70)\%$, where the quoted uncertainties are the statistical uncertainties from the fit. For the decays including a D^* the efficiency is multiplied by the probability for a D^{**} to decay with a value of $|\cos\vartheta_h|$ falling into a given bin. This factor includes the theoretical distribution discussed above as well as corrections for the different detector acceptances in the four helicity bins of up to 10%. The total number of B mesons in the data sample used for the present work is $N_{B\overline{B}} = (236.0 \pm 2.6) \times 10^6$ [10]. For the charged and neutral B mesons we assume $\Gamma(\Upsilon(4S) \to B^+B^-)/\Gamma(\Upsilon(4S) \to B^0\overline{B}^0) = 1.065 \pm 0.026$ [11].

The fit procedure has been extensively validated. The analysis procedure is tested on statistically independent MC simulated data samples and was found to reproduce the simulated signal parameters with a $\chi^2/n = 12.66/12$, where n is the number of signal parameters. Consistent fit results were also obtained when the data sample was separated into subsamples representing specific data taking periods, or separated by electron or muon modes. Furthermore the fit is tested on data by restricting it to certain decay modes, using charged or neutral D^{**} only, or combining the helicity bins.

The results of the fit are shown in Fig. 1. As expected, the contribution of the D_2^* vanishes for large values of $|\cos\vartheta_h|$ while the contribution of the D_1 is suppressed for $\cos\vartheta_h$ close to zero. The extracted yields are given in Table I.

Systematic uncertainties have been analyzed and their impact on the fitted yields have been estimated taking into account correlations between fit parameters. Effi-

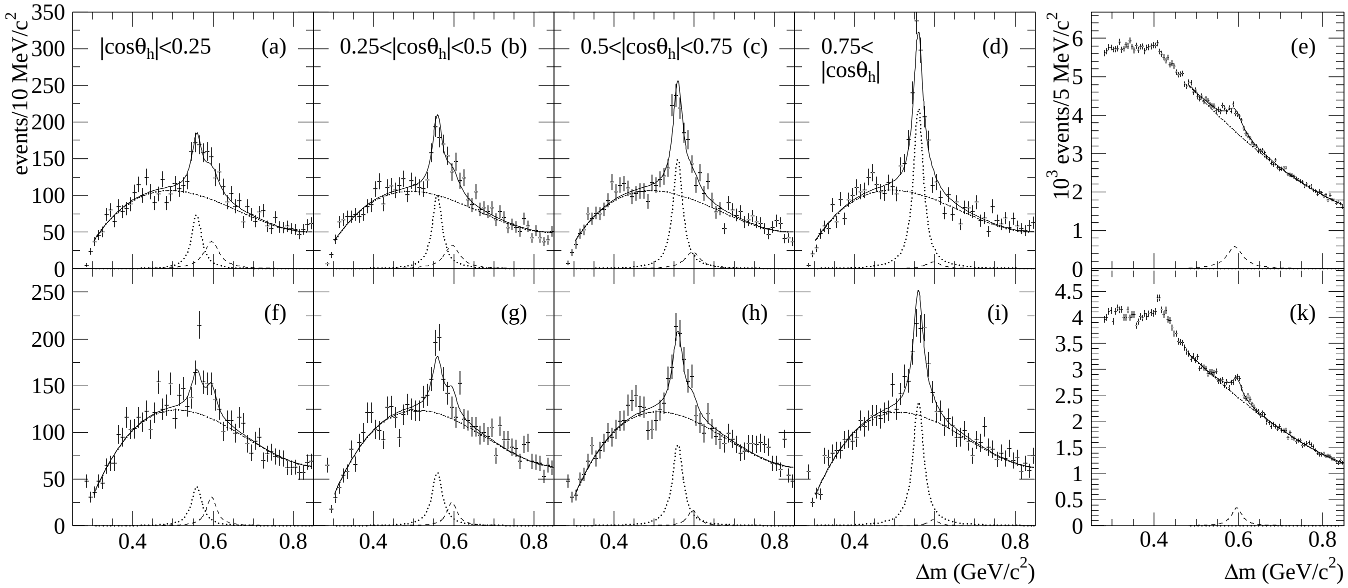

FIG. 1: Δm-spectra for the selected data and the results of the fitted functions. The solid line represents the complete fit function, dotted (D_1) and dashed (D_2^*) lines for the signal and dash-dotted the for background. (a) to (d) show the mode $D^{**0} \rightarrow D^{*+}\pi^-$ with increasing values for $|\cos\vartheta_h|$, (e) the mode $D^{**0} \rightarrow D^+\pi^-$. (f) to (i) show the corresponding bins in $|\cos\vartheta_h|$ for the mode $D^{**+} \rightarrow D^{*0}\pi^+$ and (k) the mode $D^{**+} \rightarrow D^0\pi^+$.

TABLE I: Extracted yields for the four signal modes in the five relevant Δm-spectra.

mode	$\lvert\cos\vartheta_h\rvert$	D_1^0	D_2^{*0}	D_1^+	D_2^{*+}
$D^*\pi^+$	[0 |0.25]	344	273	212	152
$D^*\pi^+$	[0.25| 0.5]	470	238	286	123
$D^*\pi^+$	[0.5 |0.75]	699	170	439	83
$D^*\pi^+$	[0.75| 1]	1027	67	668	31
$D\pi^+$		–	8414	–	3361

TABLE II: Summary of systematic uncertainties of the determination of the semileptonic branching fractions.

Source	$\Delta\mathcal{B}(B \rightarrow D^{**}\ell\nu)/\mathcal{B}(B \rightarrow D^{**}\ell\nu)[\%]$			
	D_1^0	D_2^{*0}	D_1^+	D_2^{*+}
tracking	1.76	1.39	1.03	1.14
π^0 efficiency	0.06	0.29	3.25	0.60
particle identification	2.61	2.75	3.11	1.60
MC statistics	1.80	5.61	2.50	3.32
helicity correction	0.65	0.14	0.17	0.31
number of B mesons	2.68	2.68	2.68	2.68
$\mathcal{B}(D^{*+} \rightarrow D^0\pi^+)$	0.76	0.19	0.04	0.10
$\mathcal{B}(D^{*0} \rightarrow D^0\pi^0)$	0.11	0.45	5.07	0.93
$\mathcal{B}(D^0 \rightarrow K^-\pi^+)$	1.89	0.42	1.78	2.03
$\mathcal{B}(D^+ \rightarrow K^-\pi^+\pi^+)$	0.07	2.67	0.24	0.54
modeling	2.11	4.75	3.21	1.95
bkg. parametrization	1.93	1.68	3.20	2.71
total	5.76	9.03	9.16	6.17

ciencies for reconstructing and selecting the particles of the final state are derived from Monte Carlo simulation. The simulation of the tracking and the π^0-reconstruction have been studied by comparing τ decays to one and three charged tracks and with or without a neutral pion. Uncertainties introduced by the particle identification for kaons and leptons are studied using control samples with high purities for the particles in question. The impact of the finite statistics of the simulated signal events is deduced from the fit-error of the efficiency-determination.

The uncertainty on the number of B mesons in the data set is determined as in [10]. In addition, the uncertainty in the ratio of charged and neutral B mesons produced is taken into account. The branching fractions of the decays of the D^* and the D are taken from [12].

Uncertainties introduced by the physics model which was used to simulate the MC have been addressed by reweighting the signal MC to an alternative decay model based on HQET [13]. The fit was repeated with efficiencies deduced from the re-weighted signal MC and the deviations in the results are taken as systematic uncertainties. A possible influence of the background description has been tested by varying the parametrizations. The backgrounds are alternatively described by a square root function, $f(\Delta m) = \sqrt{\Delta m - m_0}$, where m_0 is the kinematic limit, multiplied by either polynomials or exponentials in Δm. As an additional crosscheck the fit was performed with one background-parametrization while using an alternative parametrization for the determination of the efficiencies.

Table II gives a summary of the various sources of systematic uncertainty and their impact on the results. Added in quadrature the total systematic uncertainties in the semileptonic branching fractions are 6-10% depending on the D^{**} type.

In summary, we have measured the four branching fractions of B mesons decaying semileptonically into narrow D^{**} states. The D^{**} decay rates are unknown, thus we can only determine the product branching fractions

$$\begin{aligned}
\mathcal{B}(B^+ &\to D_1^0\ell^+\nu_\ell) \times \mathcal{B}(D_1^0 \to D^{*+}\pi^-) \\
&= (2.97 \pm 0.17_{\rm stat} \pm 0.17_{\rm syst}) \times 10^{-3}, \\
\mathcal{B}(B^+ &\to D_2^{*0}\ell^+\nu_\ell) \times \mathcal{B}(D_2^{*0} \to D^{(*)+}\pi^-) \\
&= (2.29 \pm 0.23_{\rm stat} \pm 0.21_{\rm syst}) \times 10^{-3}, \\
\mathcal{B}(B^0 &\to D_1^-\ell^+\nu_\ell) \times \mathcal{B}(D_1^- \to D^{*0}\pi^-) \\
&= (2.78 \pm 0.24_{\rm stat} \pm 0.25_{\rm syst}) \times 10^{-3}, \\
\mathcal{B}(B^0 &\to D_2^{*-}\ell^+\nu_\ell) \times \mathcal{B}(D_2^{*-} \to D^{(*)0}\pi^-) \\
&= (1.77 \pm 0.26_{\rm stat} \pm 0.11_{\rm syst}) \times 10^{-3}.
\end{aligned}$$

We observe all modes with significances greater than 5σ. For modes already observed we find results in agreement with previous measurements, but achieve better precisions [2, 3, 14].

For the decays of the D^{**} we measure the branching ratio $\mathcal{B}_{D/D^*} = 0.62 \pm 0.03_{\rm stat} \pm 0.02_{\rm syst}$. This ratio is in agreement with theoretical predictions [1] and previous measurements [12] but reduces the uncertainty by a factor of about four.

For the D_1 we determine the polarization parameter to be $A_{D_1} = 3.8 \pm 0.6_{\rm stat} \pm 0.8_{\rm syst}$ in agreement with unpolarized D_1 decaying purely via D wave, which gives the prediction $A_{D_1} = 3$.

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

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