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Evidence for $b \to d\gamma$ Transitions From a Sum of Exclusive Final States in the Hadronic Final State Mass Range $1.0\,\mathrm{GeV}/c^2 < M(X_d) < 1.8\,\mathrm{GeV}/c^2$.

The BABAR Collaboration

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Abstract

We present preliminary results of a search for $B \to X_d\gamma$ decays with a hadronic mass $1.0\ \mathrm{GeV}/c^2 < M(X_d) < 1.8\ \mathrm{GeV}/c^2$. We consider seven final states with up to four charged pions and one neutral pion or η, which correspond to about 50% of the total X_d fragmentation in this mass range. Based on a sample of 383 million $B\bar{B}$ events collected by the BaBar experiment at PEP-II, we measure a partial branching fraction $\sum_{X_d=1}^{7} \mathcal{B}(B \to X_d\gamma)|_{(1.0\,\mathrm{GeV}/c^2<M(X_d)<1.8\,\mathrm{GeV}/c^2)} = (3.1 \pm 0.9^{+0.6}_{-0.5} \pm 0.5)\cdot 10^{-6}$, where the uncertainties are statistical, systematic and model-dependent respectively.

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Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

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The *BABAR* Collaboration,

B. Aubert, M. Bona, D. Boutigny, Y. Karyotakis, J. P. Lees, V. Poireau, X. Prudent, V. Tisserand, A. Zghiche

Laboratoire de Physique des Particules, IN2P3/CNRS et Université de Savoie, F-74941 Annecy-Le-Vieux, France

J. Garra Tico, E. Grauges

Universitat de Barcelona, Facultat de Fisica, Departament ECM, E-08028 Barcelona, Spain

L. Lopez, A. Palano, M. Pappagallo

Università di Bari, Dipartimento di Fisica and INFN, I-70126 Bari, Italy

G. Eigen, B. Stugu, L. Sun

University of Bergen, Institute of Physics, N-5007 Bergen, Norway

G. S. Abrams, M. Battaglia, D. N. Brown, J. Button-Shafer, R. N. Cahn, Y. Groysman, R. G. Jacobsen, J. A. Kadyk, L. T. Kerth, Yu. G. Kolomensky, G. Kukartsev, D. Lopes Pegna, G. Lynch, L. M. Mir, T. J. Orimoto, I. L. Osipenkov, M. T. Ronan,[1] K. Tackmann, T. Tanabe, W. A. Wenzel

Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA

P. del Amo Sanchez, C. M. Hawkes, A. T. Watson

University of Birmingham, Birmingham, B15 2TT, United Kingdom

H. Koch, T. Schroeder

Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany

D. Walker

University of Bristol, Bristol BS8 1TL, United Kingdom

D. J. Asgeirsson, T. Cuhadar-Donszelmann, B. G. Fulsom, C. Hearty, T. S. Mattison, J. A. McKenna

University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1

A. Khan, M. Saleem, L. Teodorescu

Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom

V. E. Blinov, A. D. Bukin, V. P. Druzhinin, V. B. Golubev, A. P. Onuchin, S. I. Serednyakov, Yu. I. Skovpen, E. P. Solodov, K. Yu. Todyshev

Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia

M. Bondioli, S. Curry, I. Eschrich, D. Kirkby, A. J. Lankford, P. Lund, M. Mandelkern, E. C. Martin, D. P. Stoker

University of California at Irvine, Irvine, California 92697, USA

S. Abachi, C. Buchanan

University of California at Los Angeles, Los Angeles, California 90024, USA

S. D. Foulkes, J. W. Gary, F. Liu, O. Long, B. C. Shen,[1] G. M. Vitug, L. Zhang

University of California at Riverside, Riverside, California 92521, USA

[1]Deceased

H. P. Paar, S. Rahatlou, V. Sharma
University of California at San Diego, La Jolla, California 92093, USA

J. W. Berryhill, C. Campagnari, A. Cunha, B. Dahmes, T. M. Hong, D. Kovalskyi, J. D. Richman
University of California at Santa Barbara, Santa Barbara, California 93106, USA

T. W. Beck, A. M. Eisner, C. J. Flacco, C. A. Heusch, J. Kroseberg, W. S. Lockman, T. Schalk, B. A. Schumm, A. Seiden, M. G. Wilson, L. O. Winstrom
University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA

E. Chen, C. H. Cheng, F. Fang, D. G. Hitlin, I. Narsky, T. Piatenko, F. C. Porter
California Institute of Technology, Pasadena, California 91125, USA

R. Andreassen, G. Mancinelli, B. T. Meadows, K. Mishra, M. D. Sokoloff
University of Cincinnati, Cincinnati, Ohio 45221, USA

F. Blanc, P. C. Bloom, S. Chen, W. T. Ford, J. F. Hirschauer, A. Kreisel, M. Nagel, U. Nauenberg, A. Olivas, J. G. Smith, K. A. Ulmer, S. R. Wagner, J. Zhang
University of Colorado, Boulder, Colorado 80309, USA

A. M. Gabareen, A. Soffer,[2] W. H. Toki, R. J. Wilson, F. Winklmeier
Colorado State University, Fort Collins, Colorado 80523, USA

D. D. Altenburg, E. Feltresi, A. Hauke, H. Jasper, J. Merkel, A. Petzold, B. Spaan, K. Wacker
Universität Dortmund, Institut für Physik, D-44221 Dortmund, Germany

V. Klose, M. J. Kobel, H. M. Lacker, W. F. Mader, R. Nogowski, J. Schubert, K. R. Schubert, R. Schwierz, J. E. Sundermann, A. Volk
Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany

D. Bernard, G. R. Bonneaud, E. Latour, V. Lombardo, Ch. Thiebaux, M. Verderi
Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, F-91128 Palaiseau, France

P. J. Clark, W. Gradl, F. Muheim, S. Playfer, A. I. Robertson, J. E. Watson, Y. Xie
University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom

M. Andreotti, D. Bettoni, C. Bozzi, R. Calabrese, A. Cecchi, G. Cibinetto, P. Franchini, E. Luppi, M. Negrini, A. Petrella, L. Piemontese, E. Prencipe, V. Santoro
Università di Ferrara, Dipartimento di Fisica and INFN, I-44100 Ferrara, Italy

F. Anulli, R. Baldini-Ferroli, A. Calcaterra, R. de Sangro, G. Finocchiaro, S. Pacetti, P. Patteri, I. M. Peruzzi,[3] M. Piccolo, M. Rama, A. Zallo
Laboratori Nazionali di Frascati dell'INFN, I-00044 Frascati, Italy

A. Buzzo, R. Contri, M. Lo Vetere, M. M. Macri, M. R. Monge, S. Passaggio, C. Patrignani, E. Robutti, A. Santroni, S. Tosi
Università di Genova, Dipartimento di Fisica and INFN, I-16146 Genova, Italy

[2]Now at Tel Aviv University, Tel Aviv, 69978, Israel
[3]Also with Università di Perugia, Dipartimento di Fisica, Perugia, Italy

K. S. Chaisanguanthum, M. Morii, J. Wu
Harvard University, Cambridge, Massachusetts 02138, USA

R. S. Dubitzky, J. Marks, S. Schenk, U. Uwer
Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany

D. J. Bard, P. D. Dauncey, R. L. Flack, J. A. Nash, W. Panduro Vazquez, M. Tibbetts
Imperial College London, London, SW7 2AZ, United Kingdom

P. K. Behera, X. Chai, M. J. Charles, U. Mallik
University of Iowa, Iowa City, Iowa 52242, USA

J. Cochran, H. B. Crawley, L. Dong, V. Eyges, W. T. Meyer, S. Prell, E. I. Rosenberg, A. E. Rubin
Iowa State University, Ames, Iowa 50011-3160, USA

Y. Y. Gao, A. V. Gritsan, Z. J. Guo, C. K. Lae
Johns Hopkins University, Baltimore, Maryland 21218, USA

A. G. Denig, M. Fritsch, G. Schott
Universität Karlsruhe, Institut für Experimentelle Kernphysik, D-76021 Karlsruhe, Germany

N. Arnaud, J. Béquilleux, A. D'Orazio, M. Davier, G. Grosdidier, A. Höcker, V. Lepeltier, F. Le Diberder, A. M. Lutz, S. Pruvot, S. Rodier, P. Roudeau, M. H. Schune, J. Serrano, V. Sordini, A. Stocchi, L. Wang, W. F. Wang, G. Wormser
Laboratoire de l'Accélérateur Linéaire, IN2P3/CNRS et Université Paris-Sud 11, Centre Scientifique d'Orsay, B. P. 34, F-91898 ORSAY Cedex, France

D. J. Lange, D. M. Wright
Lawrence Livermore National Laboratory, Livermore, California 94550, USA

I. Bingham, J. P. Burke, C. A. Chavez, J. R. Fry, E. Gabathuler, R. Gamet, D. E. Hutchcroft, D. J. Payne, K. C. Schofield, C. Touramanis
University of Liverpool, Liverpool L69 7ZE, United Kingdom

A. J. Bevan, K. A. George, F. Di Lodovico, R. Sacco, M. Sigamani
Queen Mary, University of London, E1 4NS, United Kingdom

G. Cowan, H. U. Flaecher, D. A. Hopkins, S. Paramesvaran, F. Salvatore, A. C. Wren
University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom

D. N. Brown, C. L. Davis
University of Louisville, Louisville, Kentucky 40292, USA

J. Allison, N. R. Barlow, R. J. Barlow, Y. M. Chia, C. L. Edgar, G. D. Lafferty, T. J. West, J. I. Yi
University of Manchester, Manchester M13 9PL, United Kingdom

J. Anderson, C. Chen, A. Jawahery, D. A. Roberts, G. Simi, J. M. Tuggle
University of Maryland, College Park, Maryland 20742, USA

G. Blaylock, C. Dallapiccola, S. S. Hertzbach, X. Li, T. B. Moore, E. Salvati, S. Saremi
University of Massachusetts, Amherst, Massachusetts 01003, USA

R. Cowan, D. Dujmic, P. H. Fisher, K. Koeneke, G. Sciolla, M. Spitznagel, F. Taylor, R. K. Yamamoto, M. Zhao, Y. Zheng
Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA

S. E. Mclachlin,[1] P. M. Patel, S. H. Robertson
McGill University, Montréal, Québec, Canada H3A 2T8

A. Lazzaro, F. Palombo
Università di Milano, Dipartimento di Fisica and INFN, I-20133 Milano, Italy

J. M. Bauer, L. Cremaldi, V. Eschenburg, R. Godang, R. Kroeger, D. A. Sanders, D. J. Summers, H. W. Zhao
University of Mississippi, University, Mississippi 38677, USA

S. Brunet, D. Cô,té, M. Simard, P. Taras, F. B. Viaud
Université de Montréal, Physique des Particules, Montréal, Québec, Canada H3C 3J7

H. Nicholson
Mount Holyoke College, South Hadley, Massachusetts 01075, USA

G. De Nardo, F. Fabozzi,[4] L. Lista, D. Monorchio, C. Sciacca
Università di Napoli Federico II, Dipartimento di Scienze Fisiche and INFN, I-80126, Napoli, Italy

M. A. Baak, G. Raven, H. L. Snoek
NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands

C. P. Jessop, K. J. Knoepfel, J. M. LoSecco
University of Notre Dame, Notre Dame, Indiana 46556, USA

G. Benelli, L. A. Corwin, K. Honscheid, H. Kagan, R. Kass, J. P. Morris, A. M. Rahimi, J. J. Regensburger, S. J. Sekula, Q. K. Wong
Ohio State University, Columbus, Ohio 43210, USA

N. L. Blount, J. Brau, R. Frey, O. Igonkina, J. A. Kolb, M. Lu, R. Rahmat, N. B. Sinev, D. Strom, J. Strube, E. Torrence
University of Oregon, Eugene, Oregon 97403, USA

N. Gagliardi, A. Gaz, M. Margoni, M. Morandin, A. Pompili, M. Posocco, M. Rotondo, F. Simonetto, R. Stroili, C. Voci
Università di Padova, Dipartimento di Fisica and INFN, I-35131 Padova, Italy

E. Ben-Haim, H. Briand, G. Calderini, J. Chauveau, P. David, L. Del Buono, Ch. de la Vaissière, O. Hamon, Ph. Leruste, J. Malclès, J. Ocariz, A. Perez, J. Prendki
Laboratoire de Physique Nucléaire et de Hautes Energies, IN2P3/CNRS, Université Pierre et Marie Curie-Paris6, Université Denis Diderot-Paris7, F-75252 Paris, France

[4]Also with Università della Basilicata, Potenza, Italy

L. Gladney
University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA

M. Biasini, R. Covarelli, E. Manoni
Università di Perugia, Dipartimento di Fisica and INFN, I-06100 Perugia, Italy

C. Angelini, G. Batignani, S. Bettarini, M. Carpinelli,[5] R. Cenci, A. Cervelli, F. Forti, M. A. Giorgi, A. Lusiani, G. Marchiori, M. A. Mazur, M. Morganti, N. Neri, E. Paoloni, G. Rizzo, J. J. Walsh
Università di Pisa, Dipartimento di Fisica, Scuola Normale Superiore and INFN, I-56127 Pisa, Italy

J. Biesiada, P. Elmer, Y. P. Lau, C. Lu, J. Olsen, A. J. S. Smith, A. V. Telnov
Princeton University, Princeton, New Jersey 08544, USA

E. Baracchini, F. Bellini, G. Cavoto, D. del Re, E. Di Marco, R. Faccini, F. Ferrarotto, F. Ferroni, M. Gaspero, P. D. Jackson, L. Li Gioi, M. A. Mazzoni, S. Morganti, G. Piredda, F. Polci, F. Renga, C. Voena
Università di Roma La Sapienza, Dipartimento di Fisica and INFN, I-00185 Roma, Italy

M. Ebert, T. Hartmann, H. Schröder, R. Waldi
Universität Rostock, D-18051 Rostock, Germany

T. Adye, G. Castelli, B. Franek, E. O. Olaiya, W. Roethel, F. F. Wilson
Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom

S. Emery, M. Escalier, A. Gaidot, S. F. Ganzhur, G. Hamel de Monchenault, W. Kozanecki, G. Vasseur, Ch. Yèche, M. Zito
DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France

X. R. Chen, H. Liu, W. Park, M. V. Purohit, R. M. White, J. R. Wilson,
University of South Carolina, Columbia, South Carolina 29208, USA

M. T. Allen, D. Aston, R. Bartoldus, P. Bechtle, R. Claus, J. P. Coleman, M. R. Convery, J. C. Dingfelder, J. Dorfan, G. P. Dubois-Felsmann, W. Dunwoodie, R. C. Field, T. Glanzman, S. J. Gowdy, M. T. Graham, P. Grenier, C. Hast, W. R. Innes, J. Kaminski, M. H. Kelsey, H. Kim, P. Kim, M. L. Kocian, D. W. G. S. Leith, S. Li, S. Luitz, V. Luth, H. L. Lynch, D. B. MacFarlane, H. Marsiske, R. Messner, D. R. Muller, S. Nelson, C. P. O'Grady, I. Ofte, A. Perazzo, M. Perl, T. Pulliam, B. N. Ratcliff, A. Roodman, A. A. Salnikov, R. H. Schindler, J. Schwiening, A. Snyder, D. Su, S. Sun, M. K. Sullivan, K. Suzuki, S. K. Swain, J. M. Thompson, J. Va'vra, A. P. Wagner, M. Weaver, W. J. Wisniewski, M. Wittgen, D. H. Wright, A. K. Yarritu, K. Yi, C. C. Young, V. Ziegler
Stanford Linear Accelerator Center, Stanford, California 94309, USA

P. R. Burchat, A. J. Edwards, S. A. Majewski, T. S. Miyashita, B. A. Petersen, L. Wilden
Stanford University, Stanford, California 94305-4060, USA

S. Ahmed, M. S. Alam, R. Bula, J. A. Ernst, V. Jain, B. Pan, M. A. Saeed, F. R. Wappler, S. B. Zain
State University of New York, Albany, New York 12222, USA

M. Krishnamurthy, S. M. Spanier, B. J. Wogsland
University of Tennessee, Knoxville, Tennessee 37996, USA

[5]Also with Universita' di Sassari, Sassari, Italy

R. Eckmann, J. L. Ritchie, A. M. Ruland, C. J. Schilling, R. F. Schwitters
University of Texas at Austin, Austin, Texas 78712, USA

J. M. Izen, X. C. Lou, S. Ye
University of Texas at Dallas, Richardson, Texas 75083, USA

F. Bianchi, F. Gallo, D. Gamba, M. Pelliccioni
Università di Torino, Dipartimento di Fisica Sperimentale and INFN, I-10125 Torino, Italy

M. Bomben, L. Bosisio, C. Cartaro, F. Cossutti, G. Della Ricca, L. Lanceri, L. Vitale
Università di Trieste, Dipartimento di Fisica and INFN, I-34127 Trieste, Italy

V. Azzolini, N. Lopez-March, F. Martinez-Vidal,[6] D. A. Milanes, A. Oyanguren
IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain

J. Albert, Sw. Banerjee, B. Bhuyan, K. Hamano, R. Kowalewski, I. M. Nugent, J. M. Roney, R. J. Sobie
University of Victoria, Victoria, British Columbia, Canada V8W 3P6

P. F. Harrison, J. Ilic, T. E. Latham, G. B. Mohanty
Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom

H. R. Band, X. Chen, S. Dasu, K. T. Flood, J. J. Hollar, P. E. Kutter, Y. Pan, M. Pierini, R. Prepost, S. L. Wu
University of Wisconsin, Madison, Wisconsin 53706, USA

H. Neal
Yale University, New Haven, Connecticut 06511, USA

[6]Also with Universitat de Barcelona, Facultat de Fisica, Departament ECM, E-08028 Barcelona, Spain

1 INTRODUCTION

We present an experimental study of the rare decays $B \to X_d\gamma$. Within the standard model of particle physics (SM), these flavor-changing-neutral-current (FCNC) $b \to d\gamma$ transitions are forbidden at tree level; the leading-order processes are one-loop electroweak penguin diagrams (see Figure 1), where the top quark is the dominant virtual quark contribution. In the context of theories

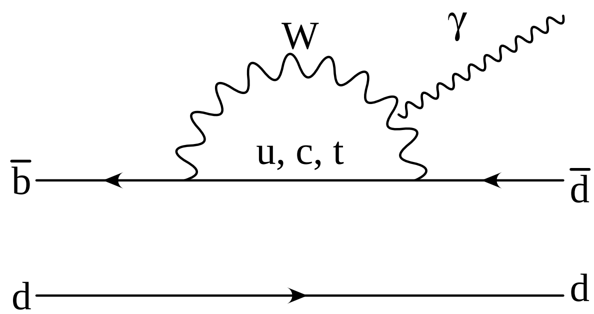

Figure 1: Feynman diagram for a $\bar{b} \to \bar{d}\gamma$ transition

beyond the SM, new virtual particles may appear in the loop, which could lead to measurable effects on experimental observables such as branching fractions and CP asymmetries [1].

Previous measurements of the exclusive decays $B^+ \to \rho^+\gamma$, $B^0 \to \rho^0\gamma$, and $B^0 \to \omega\gamma$ by the Belle [2] and *BABAR* [3] experiments found branching fractions of $\mathcal{O}(10^{-6})$, in good agreement with SM predictions [5]. In combination with the well-measured $B \to K^*\gamma$ branching fractions they also yielded measurements of the ratio of Cabbibo-Kobayashi-Maskawa (CKM) matrix elements $|V_{td}/V_{ts}|$ which are in good agreement with results independently obtained from the ratio of B_d^0 and B_s^0 mixing frequencies [4].

The experimental and theoretical uncertainties associated with the exclusive measurements are still large and there is a strong motivation to extend the experimental study to additional final states and different regions of the hadronic mass spectrum, with a measurement of the inclusive $b \to d\gamma$ transition rate as the ultimate goal. In this note we report the first study of $b \to d\gamma$ transitions using a sum of seven exclusive $X_d\gamma$ final states in the previously unaccessed hadronic mass range $1.0\,\mathrm{GeV}/c^2 < M(X_d) < 1.8\,\mathrm{GeV}/c^2$.

2 THE *BABAR* DETECTOR

The data used in this analysis were collected with the *BABAR* detector at the PEP-II asymmetric–energy e^+e^- storage ring. Charged particle trajectories are measured using a five-layer silicon vertex tracker and a 40-layer drift chamber in a 1.5-T magnetic field. Photons and electrons are detected in a CsI(Tl) crystal electromagnetic calorimeter (EMC) with photon energy resolution $\sigma_E/E = 0.023(E/\mathrm{GeV})^{-1/4} \oplus 0.019$. A ring-imaging Cherenkov detector (DIRC) is used for charged-particle identification. In order to identify muons, the magnetic flux return is instrumented with resistive plate chambers and limited streamer tubes. A detailed description of the detector can be found elsewhere [6].

3 EVENT RECONSTRUCTION AND SELECTION

We exclusively reconstruct seven $b \to d\gamma$ decay modes with up to four charged pions and one neutral pion or eta in the final state: $B^0 \to \pi^+\pi^-\gamma$, $B^+ \to \pi^+\pi^0\gamma$, $B^+ \to \pi^+\pi^-\pi^+\gamma$, $B^0 \to \pi^+\pi^-\pi^0\gamma$, $B^0 \to \pi^+\pi^-\pi^+\pi^-\gamma$, $B^+ \to \pi^+\pi^-\pi^+\pi^0\gamma$, $B^+ \to \pi^+\eta\gamma$ [8].

An important source of background is due to continuum events ($e^+e^- \to q\bar{q}$, with $q = u, d, s, c$) that contain a high-energy photon from π^0 or η decays or from initial-state radiation. There is also background from combinatorial B decays. These include $B \to X_d\pi^0$ and $B \to X_d\eta$ processes that produce a high-energy photon in the π^0 or η decay, as well as $B \to X_s\gamma$ decays where a $K^\pm$ is misidentified as a $\pi^\pm$. Background suppression cuts have been optimized for maximum statistical sensitivity $S/\sqrt(S+B)$, where S and B are the rates for signal and background events, using Monte Carlo (MC) simulated event samples, and assuming an inclusive $b \to d\gamma$ branching fraction of 1.0×10^{-5}. Of particular concern are backgrounds from B meson decays that resemble the signal.

The photon from the signal B decay is identified as a localized energy deposit in the calorimeter with energy $1.15 < E^*_\gamma < 3.5$ GeV in the center-of-mass (CM) frame. The energy deposit must not be associated with any reconstructed charged track, be well isolated from other EMC deposits, and meet a number of additional requirements designed to eliminate background from hadronic showers and small-angle photon pairs. We veto any photons that can form a π^0 (η) candidate by association with another detected photon of energy greater than 30 (250) MeV by requiring that the two–photon invariant mass be outside the range of 105 MeV/c^2–155 MeV/c^2 (500 MeV/c^2–590 MeV/c^2).

Charged pion candidates are selected from well-reconstructed tracks with a minimum momentum in the laboratory frame of 300 MeV/c. In order to reduce backgrounds from charged kaons produced in $b \to s\gamma$ processes, a $\pi^\pm$ selection algorithm is applied, combining DIRC information with the energy loss measured in the tracking system. At a typical pion energy of 1 GeV the pion selection efficiency is over 85% and the Kaon mis-identification rate is less than 2%.

π^0 (η) candidates are formed from pairs of photons with energies greater than 20 MeV, with an invariant mass $117 < m_{\gamma\gamma} < 145$ MeV/c^2 ($470 < m_{\gamma\gamma} < 620$ MeV/c^2). We require π^0 and η candidates to have a momentum greater than 300 MeV/c.

The selected $\pi^\pm$, π^0, η, and high-energy photon candidates are combined to form B meson candidates consistent with one of the seven signal decays. Here, the charged pions are combined to form a common vertex, where we require the vertex probability be greater than 2%. The mass of the hadronic system is required to be in the range 1.0 GeV/$c^2 < M(X_d) < 1.8$ GeV/c^2. We define $\Delta E \equiv E^*_B - E^*_{\rm beam}$, where E^*_B is the CM energy of the B-meson candidate and $E^*_{\rm beam}$ is the CM beam energy. We also use the beam-energy-substituted mass $m_{\rm ES} \equiv \sqrt{E^{*2}_{\rm beam} - \vec{\rm p}^{\,*2}_B}$, where $\vec{\rm p}^{\,*}_B$ is the CM momentum of the B candidate. Signal events are expected to have a ΔE distribution centered at zero with a resolution of about 30 MeV, and an $m_{\rm ES}$ distribution centered at the mass of the B meson, m_B, with a resolution of 3 MeV/c^2. We consider candidates in the ranges $-0.3\,\text{GeV} < \Delta E < 0.2\,\text{GeV}$ and $m_{\rm ES} > 5.22$ GeV/c^2 to incorporate sidebands that allow the combinatorial background yields to be extracted by a fit to the data.

Contributions from continuum background processes are reduced by considering only events for which the ratio R_2 of second-to-zeroth order Fox-Wolfram moments [7] is less than 0.9. To further discriminate between the jet-like continuum background and the more spherically-symmetric signal events, we compute the angle θ_T between the photon and the thrust axis of the rest of the event (ROE) in the CM frame and require $|cos(\theta_T)| < 0.8$. The ROE is defined as all the charged tracks and neutral energy deposits in the calorimeter that are not used to reconstruct the B candidate.

The quantity $cos(\theta_T)$ and twelve other variables that distinguish between signal and continuum events are combined in a neural network (NN): R_2', which is R_2 in the frame recoiling against the photon momentum, is used to suppress events with initial-state radiation. We also compute the B-meson production angle θ_B^* with respect to the beam axis in the CM frame, and the Legendre moments $L_i \equiv \sum_j p_j^* \cdot |\cos\theta_j^*|^i / \sum_j p_j^*$ and $\tilde{L}_i \equiv \sum_j p_j^* \cdot |\sin\theta_j^*|^i / \sum_j p_j^*$, where p_j^* and θ_j^* are the momentum and angle with respect to a given axis, respectively, for each particle j in the ROE. We use L_1 with respect to the ROE thrust axis, as well as L_2, L_3, $\tilde{L}_2$, and $\tilde{L}_3$ with respect to the high–energy photon direction as NN input. Differences in lepton and kaon production between background and B decays are exploited by including several flavor-tagging variables described in [10]. We select events for which the NN yields an output value greater than 0.83; this corresponds to signal and continuum background efficiencies of about 50% and 0.5% respectively.

The expected average number of candidates per selected signal event is 1.75. In events with multiple candidates the one with the reconstructed $\pi^0(\eta)$ mass closest to the nominal [9] is retained. For events containing no $\pi^0(\eta)$ the candidate with the highest vertex probability is retained.

From simulated signal events with $1.0\,\mathrm{GeV}/c^2 < M_{X_d} < 1.8\,\mathrm{GeV}/c^2$, applying all the selection criteria described above, we find an overall signal selection efficiency of 7.5%.

4 MAXIMUM LIKELIHOOD FIT

The signal content of the data is determined by means of a two-dimensional unbinned maximum likelihood fit to the ΔE and m_{ES} distributions. We consider the following contributions: signal, combinatorial backgrounds from continuum and $B\bar{B}$ background processes, $B \to X_d\pi^0/\eta$ decays, $B \to X_s\gamma$ decays, and self-crossfeed from mis-reconstructed $B \to X_d\gamma$ decays. The likelihood function is defined as

$$\mathcal{L} = \exp\left(-\sum_{i=1}^{N_{\mathrm{hyp}}} n_i\right) \cdot \left[\prod_{j=1}^{N_{dat}} \left(\sum_{i=1}^{N_{\mathrm{hyp}}} n_i \mathcal{P}_i(\vec{x}_j;\ \vec{\alpha}_i)\right)\right] . \tag{1}$$

Here, n_i are the event yields for each of the signal and background hypotheses and N_{dat} is the number of events observed in data; P_i is the probability density function (PDF) for hypothesis i, which depends on the fit observables $\vec{x}_j = (\Delta E, m_{\mathrm{ES}})$ and a set of parameters $\vec{\alpha}_i$.

The functional form of each PDF is determined from MC simulated events. For the $B \to X_d\gamma$ self-crossfeed component we use a binned two-dimensional $(\Delta E, m_{\mathrm{ES}})$ distribution as the input PDF, while for the other hypotheses we obtain the PDFs from unbinned one-dimensional fits to the ΔE and m_{ES} distributions respectively. For the signal, the m_{ES} spectrum is described by a Crystal Ball function [12], and the ΔE distribution is parametrized as an asymmetric, variable-width Gaussian $f(x) = \exp\left[-(x-\mu)^2/(2\sigma_{L,R}^2 + \alpha_{L,R}(x-\mu)^2)\right]$, where μ is the peak position of the distribution, $\sigma_{L,R}$ are the widths left and right of the peak, and $\alpha_{L,R}$ are measures of the tails on the left and right sides of the peak. The contributions from $B \to X_d\pi^0/\eta$ and $B \to X_s\gamma$ decays are both modeled by adding a Gaussian distribution to an ARGUS function [11] for m_{ES} and a Gaussian distribution to the second-order polynomial describing the background for ΔE. The Gaussian peaks in ΔE are displaced by $\approx 80\,\mathrm{MeV}$ for $B \to X_d\pi^0/\eta$ by the missing photon, and by $\approx 100\,\mathrm{MeV}$ for $B \to X_s\gamma$ by the kaon mis-identification. A combined PDF is defined for the remaining B backgrounds and continuum processes using the sum of a Gaussian and an ARGUS function for m_{ES} and a second-order polynomial for ΔE. The Gaussian component allows for a small component of B decays that peaks in m_{ES} but not in ΔE.

In the likelihood fit the $m_{\rm ES}$ ARGUS slope parameter and the ΔE polynomial coefficients of the combined background PDF are free parameters, likewise the yields for this background and for the signal. All other fit parameters are fixed to the values obtained from the MC samples.

5 VALIDATION OF THE ANALYSIS PROCEDURE

In order to validate the analysis procedure, we embed signal MC events in backgrounds randomly generated from the background PDFs. The embedded events include both the correctly reconstructed and the self-crossfeed signal contributions. For different numbers of embedded signal events we determine the pulls on the yield and the statistical error from the fit. We find a bias in the fitted yield of +24% of the statistical error. We correct the final fit result for this bias and treat it as a systematic error.

To check our analysis on data we select $B \to K^*\gamma$ decays, using the K^* decay modes $K^{*+} \to K^+\pi^0$ and $K^{*0} \to K^+\pi^-$. The selection is the same as for the two signal modes $B^0 \to \pi^+\pi^-\gamma$ and $B^+ \to \pi^+\pi^0\gamma$, except that the $\pi^\pm$ identification requirements are replaced with a charged kaon selection, and the mass range is $0.6\,\mathrm{GeV}/c^2 < M(X_s) < 1.0\,\mathrm{GeV}/c^2$. In the fit procedure described in the previous section we include a $B \to X_s\gamma$ self-crossfeed component and a $B \to X_s\pi^0/\eta$ background, but not a $B \to X_d\gamma$ misidentification component because this is expected to be negligible. $B \to K^*\gamma$ has a large signal yield, so we use this fit to determine the signal shape in data by allowing the means and widths of the signal PDFs to vary. We find 1680 ± 51 $B \to K^*\gamma$ events in the *BABAR* data, where this error is purely statistical. This is in excellent agreement with the expectation of 1616 ± 28 events based on the previously measured branching fraction of $\mathcal{B}(B \to K^*\gamma) = (4.02 \pm 0.33) \times 10^{-5}$ [14].

As a further check on data we perform the signal analysis for the decays $B^0 \to \pi^+\pi^-\gamma$, $B^+ \to \pi^+\pi^0\gamma$, and $B^0 \to \pi^+\pi^-\pi^0\gamma$ in the hadronic mass range $0.6\,\mathrm{GeV}/c^2 < M(X_d) < 1.0\,\mathrm{GeV}/c^2$, which contains the $\rho^0, \rho^\pm$ and ω resonances. In this fit we include all the contributions in a similar way to the $B \to X_d\gamma$ analysis in the higher mass region, and fix the signal PDF shape to the values obtained from the $B \to K^*\gamma$ fit. We obtain a combined $B \to (\rho,\omega)\gamma$ signal of $73 \pm 25(\mathrm{stat.})$ events corresponding to a statistical significance of 2.9σ. This is consistent with the 66 ± 26 events expected from the average of previous branching fraction measurements by *BABAR* and Belle of $\mathcal{B}(B \to (\rho,\omega)\gamma) = (1.28 \pm 0.21) \times 10^{-6}$ [14]. Note that we do not make use of the resonance mass or the decay helicity angle to discriminate against backgrounds, so we do not expect this measurement to be as precise as the exclusive $B \to (\rho,\omega)\gamma$ analyses. Figure 2 shows a comparison of the PDF component shapes (curves) to the data (points).

6 RESULTS

Finally we perform the full fit for the sum of all seven decay modes in the hadronic mass range $1.0\,\mathrm{GeV}/c^2 < M(X_d) < 1.8\ \mathrm{GeV}/c^2$, again using the signal PDFs from $B \to K^*\gamma$.

Figure 3 shows a comparison of the PDF component shapes (curves) to the data (points). For each plot, a cut is applied to the variable not plotted around the signal peak.

Figure 4 shows a comparison of the PDF shapes (solid curves) to the data using the event-weighting technique described in Ref. [13] to subtract the fitted background. For each plot, we perform a fit excluding the variable being plotted and use the fitted yields and covariance matrix to determine the relative probability that an event is signal or background. The distribution is

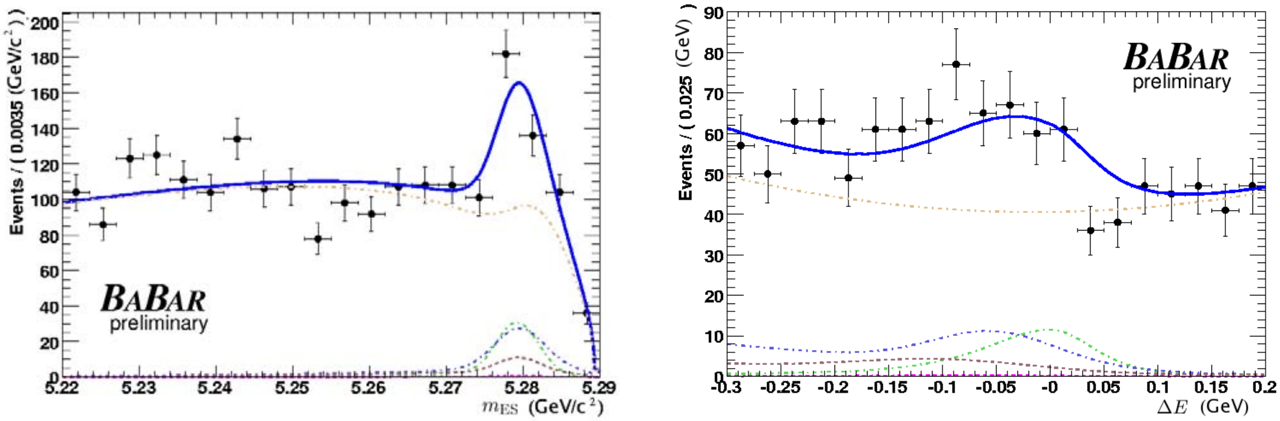

Figure 2: Projections of $m_{\rm ES}$ with $-0.1\,\mathrm{GeV} < \Delta E < 0.05\,\mathrm{GeV}$ (left) and ΔE with $5.275\,\mathrm{GeV}/c^2 < m_{\rm ES} < 5.286\,\mathrm{GeV}/c^2$ (right) in the $B \to (\rho,\omega)\gamma$ fit to data (points with statistical errors). The curves represent the PDFs used in the fit with the combined PDF in solid blue. The dashed lines represent the individual PDFs with with signal component in green, signal cross-feed in pink, $b \to s\gamma$ background in blue, $B \to X_d\pi^0/\eta$ background in brown and background in orange.

normalized to the yield for the given component and can be compared directly to the assumed PDF shape. We find good agreement between the data and the PDFs.

We find a signal yield of 178 ± 53 events and a background of 27670 ± 173 events in the full fit. Taking only statistical uncertainties into account, this corresponds to a signal significance of 3.4σ. We calculate the partial branching fraction summed over the seven modes in the mass region $1.0\,\mathrm{GeV}/c^2 < M(X_d) < 1.8\,\mathrm{GeV}/c^2$ using the following formula:

$$\sum_{X_d=1}^{7} \mathcal{B}(B \to X_d\gamma)|_{(1.0\,\mathrm{GeV}/c^2 < M(X_d) < 1.8\,\mathrm{GeV}/c^2)} = \frac{n_{sig}}{2\ \epsilon\ n_{B\overline{B}}}; \tag{2}$$

where n_{sig} is the number of fitted signal events, ϵ is the signal selection efficiency, $n_{B\overline{B}}$ is the number of $B\overline{B}$ pairs in the dataset, and the factor 2 is to account for the possibility of either B decaying into a signal mode. We obtain the following result:

$$\sum_{X_d=1}^{7} \mathcal{B}(B \to X_d\gamma)|_{(1.0\,\mathrm{GeV}/c^2 < M(X_d) < 1.8\,\mathrm{GeV}/c^2)} = [3.1 \pm 0.9(stat.)] \cdot 10^{-6}\,; \tag{3}$$

The relevant systematic uncertainties are discussed below.

7 SYSTEMATIC UNCERTAINTIES

Table 1 gives an overview of the contributions to the systematic uncertainties. These are associated with the signal reconstruction efficiency, the modeling of the signal and $B\overline{B}$ background PDFs in the likelihood fit, and the modeling of the $B \to X_d\gamma$ spectrum and the fragmentation of the X_d system.

The systematic errors affecting the signal efficiency includes uncertainties on tracking, particle identification, γ and π^0 reconstruction, the π^0/η veto, and the neural network selection. These

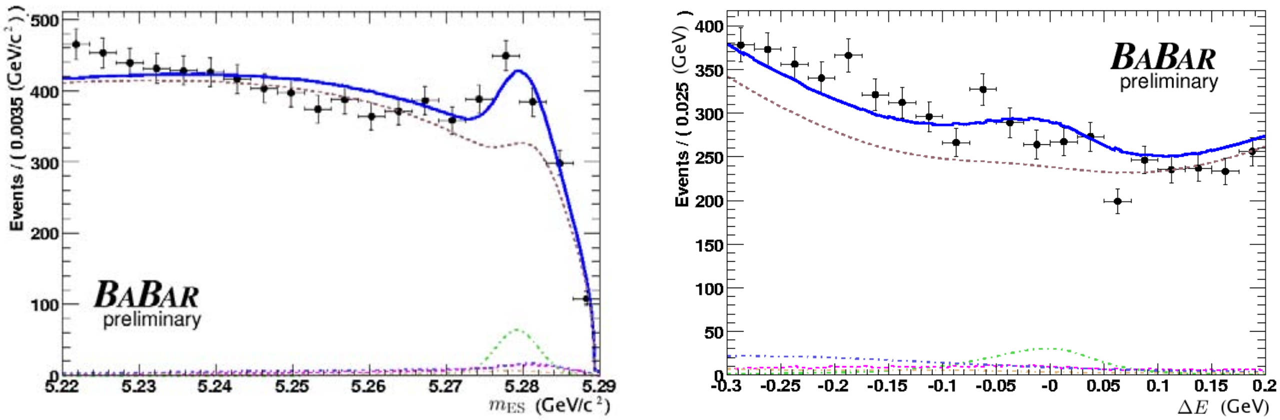

Figure 3: Projections of m_{ES} with $-0.1\,\mathrm{GeV} < \Delta E < 0.05\,\mathrm{GeV}$ (left) and ΔE with $5.275\,\mathrm{GeV}/c^2 < m_{\mathrm{ES}} < 5.286\,\mathrm{GeV}/c^2$ (right) in the $b \to d\gamma$ fit to data. The curves represent the PDFs used in the fit with the combined PDF in solid blue. The dashed lines represent the individual PDFs with with signal component in green, signal cross-feed in pink, $b \to s\gamma$ background in blue, $B \to X_d\pi^0/\eta$ background in orange and background in brown.

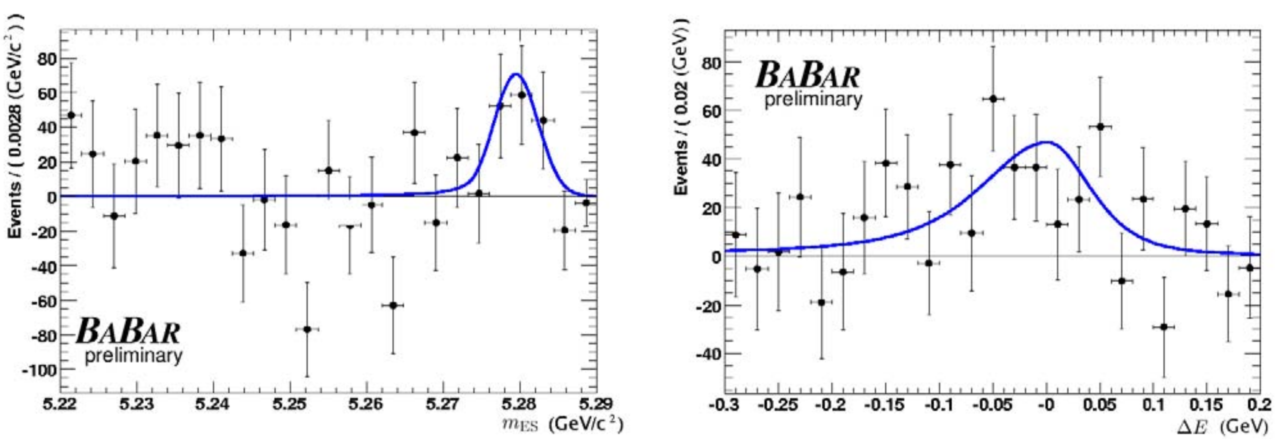

Figure 4: Signal distributions of m_{ES} (left) and ΔE (right) for $B \to X_d\gamma$ in the range $1.0\,\mathrm{GeV}/c^2 < M(X_d) < 1.8\,\mathrm{GeV}/c^2$ with the background subtraction as described in the text. The curves represent the PDFs used in the fit, normalized to the fitted yield.

uncertainties are evaluated using independent data and MC-simulated event samples. They give a combined systematic error of 6.5% when added in quadrature.

To estimate the uncertainties related to the signal and background yields we vary the parameters of the PDFs that are fixed in the fit. For the signal PDF the means and widths are varied within the range allowed by the fit to the $B \to K^*\gamma$ data. Other fixed PDF parameters are fluctuated within their statistical errors. The combination gives errors of $\pm 13\%$ on the signal yield.

All relative and absolute normalizations of background components that are fixed in the fit are also varied. The absolute normalizations of the $B \to X_d\gamma$ cross feed, $B \to X_s\gamma$, and $B \to X_d\pi^0/\eta$

Table 1: Fractional systematic errors of the measured branching fraction.

Source	Relative uncertainty (%)
Tracking efficiency	1.7
Charged-particle identification	2.0
Photon selection	2.5
π^0 and η reconstruction	1.7
π^0 and η veto	1.0
NN efficiency	5.0
PDF shapes	13.0
B background normalization	$^{+10.5}_{-3.0}$
Fit bias	7.1
B counting	1.1
Combined	$^{+19.3}_{-16.5}$
Signal model	3.4
X_d fragmentation model	13.6
Combined	14.7

components are changed by ±50%, ±20%, and ±100% respectively; and the relative contribution of the remaining B decays to the combined background component is varied by ±20%. The full size of the bias on the signal yield observed in MC experiments (see Section 5), is taken as a systematic uncertainty of the fit procedure.

There is a small 1.1% uncertainty on the overall normalization associated with the the total number of $B\overline{B}$ pairs in the underlying data sample.

The impact of the assumed X_d spectrum on the efficiency is studied by using two different sets of values for the kinetic parameters of the Kagan-Neubert model [15] $(m_b, \mu_\pi^2) = (4.65, -0.50)$ and $(4.80, -0.35)$. These are consistent with fits of $B \to X_s\gamma$ data [16]. The default fragmentation model for the X_d is JETSET [17], known not to give a good description of the distribution of final states in $B \to X_s\gamma$ [18]. To estimate the uncertainty associated with the fragmentation model, we re-weight the relative contributions of the seven signal modes according to results obtained in [18] for the corresponding $B \to X_s\gamma$ decays, and take the resulting change in the signal yield as a systematic error. Combining these two uncertainties, we assign a systematic error of 14.7/the modeling of the signal.

8 SUMMARY

In this paper we have demonstrated the feasibility of measuring $B \to X_d\gamma$ decays with a semi-inclusive technique using a sum of seven exclusive final state in the mass range $1.0\,\mathrm{GeV}/c^2 < M(X_d) < 1.8\,\mathrm{GeV}/c^2$ and presented the first evidence for $b \to d\gamma$ transitions in this mass range. We find 178 ± 53 signal events.

We measure a partial branching fraction $\sum_{X_d=1}^{7} \mathcal{B}(B \to X_d\gamma)|_{(1.0\,\mathrm{GeV}/c^2<M(X_d)<1.8\,\mathrm{GeV}/c^2)} =$

$(3.1 \pm 0.9^{+0.6}_{-0.5} \pm 0.5) \cdot 10^{-6}$, where the uncertainties are statistical, systematic and model respectively. Including statistical and systematic uncertainties only, this corresponds to a signal significance of 3.1σ.

9 OUTLOOK

In the future, the inclusive $b \to d\gamma$ transition rate can be measured. This will require further study to:

- Extend the current measurement to the mass region $0.6\,\mathrm{GeV}/c^2 < M(X_d) < 1.0\,\mathrm{GeV}/c^2$, which has been used as a control sample in this analysis with only three decay modes reconstructed. We can measure the seven decay modes over both ranges.
- Correct for the part of the X_d fragmentation that is not reconstructed by the seven decay modes. Based on MC simulation and the JETSET model we expect the measured seven modes to account for about 50% of the the hadronic mass region $1.0\,\mathrm{GeV}/c^2 < M(X_d) < 1.8\,\mathrm{GeV}/c^2$.
- Extrapolate to the full mass region. Assuming the shape of the hadronic mass spectrum is the same for $b \to d\gamma$ as for $b \to s\gamma$ decays [18], the mass region $0.6\,\mathrm{GeV}/c^2 - 1.8\,\mathrm{GeV}/c^2$ comprises roughly 60% of the spectrum.

Further, the extraction of the ratio $|V_{td}/V_{ts}|$ can be performed by comparing the branching fractions for $b \to d\gamma$ and $b \to s\gamma$ over the experimentally accessible final states and hadronic mass range. By measuring this ratio over a larger hadronic mass range, and with a larger set of final states it should be possible to reduce the theoretical uncertainties compared to the ratio of $B \to \rho\gamma$ and $B \to K^*\gamma$ decays.

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