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Observation of orbitally excited B-s  
mesons

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## Observation of Orbitally Excited $B_s$ Mesons

T. Aaltonen,<sup>23</sup> A. Abulencia,<sup>24</sup> J. Adelman,<sup>13</sup> T. Akimoto,<sup>54</sup> M. G. Albrow,<sup>17</sup> B. Álvarez González,<sup>11</sup> S. Amerio,<sup>42</sup> D. Amidei,<sup>34</sup> A. Anastassov,<sup>51</sup> A. Annovi,<sup>19</sup> J. Antos,<sup>14</sup> G. Apollinari,<sup>17</sup> A. Apresyan,<sup>47</sup> T. Arisawa,<sup>56</sup> A. Artikov,<sup>15</sup> W. Ashmanskas,<sup>17</sup> A. Attal,<sup>3</sup> A. Aurisano,<sup>52</sup> F. Azfar,<sup>41</sup> P. Azzi-Bacchetta,<sup>42</sup> P. Azzurri,<sup>45</sup> N. Bacchetta,<sup>42</sup> W. Badgett,<sup>17</sup> A. Barbaro-Galtieri,<sup>28</sup> V. E. Barnes,<sup>47</sup> B. A. Barnett,<sup>25</sup> S. Baroiant,<sup>7</sup> V. Bartsch,<sup>30</sup> G. Bauer,<sup>32</sup> P.-H. Beauchemin,<sup>33</sup> F. Bedeschi,<sup>45</sup> P. Bednar,<sup>14</sup> S. Behari,<sup>25</sup> G. Bellettini,<sup>45</sup> J. Bellinger,<sup>58</sup> A. Belloni,<sup>22</sup> D. Benjamin,<sup>16</sup> A. Beretvas,<sup>17</sup> J. Beringer,<sup>28</sup> T. Berry,<sup>29</sup> A. Bhatti,<sup>49</sup> M. Binkley,<sup>17</sup> D. Bisello,<sup>42</sup> I. Bizjak,<sup>30</sup> R. E. Blair,<sup>2</sup> C. Blocker,<sup>6</sup> B. Blumenfeld,<sup>25</sup> A. Bocci,<sup>16</sup> A. Bodek,<sup>48</sup> V. Boisvert,<sup>48</sup> G. Bolla,<sup>47</sup> A. Bolshov,<sup>32</sup> D. Bortoletto,<sup>47</sup> J. Boudreau,<sup>46</sup> A. Boveia,<sup>10</sup> B. Brau,<sup>10</sup> L. Brigliadori,<sup>5</sup> C. Bromberg,<sup>35</sup> E. Brubaker,<sup>13</sup> J. Budagov,<sup>15</sup> H. S. Budd,<sup>48</sup> S. Budd,<sup>24</sup> K. Burkett,<sup>17</sup> G. Busetto,<sup>42</sup> P. Bussey,<sup>21</sup> A. Buzatu,<sup>33</sup> K. L. Byrum,<sup>2</sup> S. Cabrera,<sup>16,r</sup> M. Campanelli,<sup>35</sup> M. Campbell,<sup>34</sup> F. Canelli,<sup>17</sup> A. Canepa,<sup>44</sup> D. Carlsmith,<sup>58</sup> R. Carosi,<sup>45</sup> S. Carrillo,<sup>18,l</sup> S. Carron,<sup>33</sup> B. Casal,<sup>11</sup> M. Casarsa,<sup>17</sup> A. Castro,<sup>5</sup> P. Catastini,<sup>45</sup> D. Cauz,<sup>53</sup> M. Cavalli-Sforza,<sup>3</sup> A. Cerri,<sup>28</sup> L. Cerrito,<sup>30,p</sup> S. H. Chang,<sup>27</sup> Y. C. Chen,<sup>1</sup> M. Chertok,<sup>7</sup> G. Chiarelli,<sup>45</sup> G. Chlachidze,<sup>17</sup> F. Chlebana,<sup>17</sup> K. Cho,<sup>27</sup> D. Chokheli,<sup>15</sup> J. P. Chou,<sup>22</sup> G. Choudalakis,<sup>32</sup> S. H. Chuang,<sup>51</sup> K. Chung,<sup>12</sup> W. H. Chung,<sup>58</sup> Y. S. Chung,<sup>48</sup> C. I. Ciobanu,<sup>24</sup> M. A. Ciocci,<sup>45</sup> A. Clark,<sup>20</sup> D. Clark,<sup>6</sup> G. Compostella,<sup>42</sup> M. E. Convery,<sup>17</sup> J. Conway,<sup>7</sup> B. Cooper,<sup>30</sup> K. Copic,<sup>34</sup> M. Cordelli,<sup>19</sup> G. Cortiana,<sup>42</sup> F. Crescioli,<sup>45</sup> C. Cuenca Almenar,<sup>7,r</sup> J. Cuevas,<sup>11,o</sup> R. Culbertson,<sup>17</sup> J. C. Cully,<sup>34</sup> D. 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Huston,<sup>35</sup> J. Incandela,<sup>10</sup> G. Introzzi,<sup>45</sup> M. Iori,<sup>50</sup> A. Ivanov,<sup>7</sup> B. Iyutin,<sup>32</sup> E. James,<sup>17</sup> B. Jayatilaka,<sup>16</sup> D. Jeans,<sup>50</sup> E. J. Jeon,<sup>27</sup> S. Jindariani,<sup>18</sup> W. Johnson,<sup>7</sup> M. Jones,<sup>47</sup> K. K. Joo,<sup>27</sup> S. Y. Jun,<sup>12</sup> J. E. Jung,<sup>27</sup> T. R. Junk,<sup>24</sup> T. Kamon,<sup>52</sup> D. Kar,<sup>18</sup> P. E. Karchin,<sup>57</sup> Y. Kato,<sup>40</sup> R. Kephart,<sup>17</sup> U. Kerzel,<sup>26</sup> V. Khotilovich,<sup>52</sup> B. Kilminster,<sup>38</sup> D. H. Kim,<sup>27</sup> H. S. Kim,<sup>27</sup> J. E. Kim,<sup>27</sup> M. J. Kim,<sup>17</sup> S. B. Kim,<sup>27</sup> S. H. Kim,<sup>54</sup> Y. K. Kim,<sup>13</sup> N. Kimura,<sup>54</sup> L. Kirsch,<sup>6</sup> S. Klimenko,<sup>18</sup> M. Klute,<sup>32</sup> B. Knuteson,<sup>32</sup> B. R. Ko,<sup>16</sup> S. A. Koay,<sup>10</sup> K. Kondo,<sup>56</sup> D. J. Kong,<sup>27</sup> J. Konigsberg,<sup>18</sup> A. Korytov,<sup>18</sup> A. V. Kotwal,<sup>16</sup> J. Kraus,<sup>24</sup> M. Kreps,<sup>26</sup> J. Kroll,<sup>44</sup> N. Krumnack,<sup>4</sup> M. Kruse,<sup>16</sup> V. Krutelyov,<sup>10</sup> T. Kubo,<sup>54</sup> S. E. Kuhlmann,<sup>2</sup> T. Kuhr,<sup>26</sup> N. P. Kulkarni,<sup>57</sup> Y. Kusakabe,<sup>56</sup> S. Kwang,<sup>13</sup> A. T. Laasanen,<sup>47</sup> S. Lai,<sup>33</sup> S. Lami,<sup>45</sup> S. Lammel,<sup>17</sup> M. Lancaster,<sup>30</sup> R. L. Lander,<sup>7</sup> K. Lannon,<sup>38</sup> A. Lath,<sup>51</sup> G. Latino,<sup>45</sup> I. Lazzizzera,<sup>42</sup> T. LeCompte,<sup>2</sup> J. Lee,<sup>48</sup> J. Lee,<sup>27</sup> Y. J. Lee,<sup>27</sup> S. W. Lee,<sup>52,q</sup> R. Lefèvre,<sup>20</sup> N. Leonardo,<sup>32</sup> S. Leone,<sup>45</sup> S. Levy,<sup>13</sup> J. D. Lewis,<sup>17</sup> C. Lin,<sup>59</sup> C. S. Lin,<sup>28</sup> M. Lindgren,<sup>17</sup> E. Lipeles,<sup>9</sup> A. Lister,<sup>7</sup> D. O. Litvintsev,<sup>17</sup> T. Liu,<sup>17</sup> N. S. Lockyer,<sup>44</sup> A. Loginov,<sup>59</sup> M. Loreti,<sup>42</sup> L. Lovas,<sup>14</sup> R.-S. Lu,<sup>1</sup> D. Lucchesi,<sup>42</sup> J. Lueck,<sup>26</sup> C. Luci,<sup>50</sup> P. Lujan,<sup>28</sup> P. Lukens,<sup>17</sup> G. Lungu,<sup>18</sup> L. Lyons,<sup>41</sup> J. Lys,<sup>28</sup> R. Lysak,<sup>14</sup> E. Lytken,<sup>47</sup> P. Mack,<sup>26</sup> D. MacQueen,<sup>33</sup> R. Madrak,<sup>17</sup> K. Maeshima,<sup>17</sup> K. Makhoul,<sup>32</sup> T. Maki,<sup>23</sup> P. Maksimovic,<sup>25</sup> S. Malde,<sup>41</sup> S. Malik,<sup>30</sup> G. Manca,<sup>29</sup> A. Manousakis,<sup>15,a</sup> F. Margaroli,<sup>47</sup> C. Marino,<sup>26</sup> C. P. Marino,<sup>24</sup> A. Martin,<sup>59</sup> M. Martin,<sup>25</sup> V. Martin,<sup>21,j</sup> M. Martínez,<sup>3</sup> R. Martínez-Ballarín,<sup>31</sup> T. Maruyama,<sup>54</sup> P. Mastrandrea,<sup>50</sup> T. Masubuchi,<sup>54</sup> M. E. Mattson,<sup>57</sup> P. Mazzanti,<sup>5</sup> K. S. McFarland,<sup>48</sup> P. McIntyre,<sup>52</sup> R. McNulty,<sup>29,i</sup> A. Mehta,<sup>29</sup> P. Mehtala,<sup>23</sup> S. Menzemer,<sup>11,k</sup> A. Menzione,<sup>45</sup> P. Merkel,<sup>47</sup> C. Mesropian,<sup>49</sup> A. Messina,<sup>35</sup> T. Miao,<sup>17</sup> N. Miladinovic,<sup>6</sup> J. Miles,<sup>32</sup> R. Miller,<sup>35</sup> C. Mills,<sup>22</sup> M. Milnik,<sup>26</sup> A. Mitra,<sup>1</sup> G. Mitselmakher,<sup>18</sup> H. Miyake,<sup>54</sup> S. Moed,<sup>22</sup> N. Moggi,<sup>5</sup> C. S. Moon,<sup>27</sup> R. Moore,<sup>17</sup> M. Morello,<sup>45</sup> P. Movilla Fernandez,<sup>28</sup> J. Mülmenstädt,<sup>28</sup> A. Mukherjee,<sup>17</sup> Th. Müller,<sup>26</sup> R. Mumford,<sup>25</sup> P. Murat,<sup>17</sup> M. Mussini,<sup>5</sup> J. Nachtman,<sup>17</sup> Y. Nagai,<sup>54</sup> A. Nagano,<sup>54</sup> J. Naganoma,<sup>56</sup> K. Nakamura,<sup>54</sup> I. Nakano,<sup>39</sup> A. Napier,<sup>55</sup> V. Necula,<sup>16</sup> C. Neu,<sup>44</sup> M. S. Neubauer,<sup>24</sup>

J. Nielsen,<sup>28,f</sup> L. Nodulman,<sup>2</sup> M. Norman,<sup>9</sup> O. Norniella,<sup>24</sup> E. Nurse,<sup>30</sup> S. H. Oh,<sup>16</sup> Y. D. Oh,<sup>27</sup> I. Oksuzian,<sup>18</sup> T. Okusawa,<sup>40</sup> R. Oldeman,<sup>29</sup> R. Orava,<sup>23</sup> K. Osterberg,<sup>23</sup> S. Pagan Griso,<sup>42</sup> C. Pagliarone,<sup>45</sup> E. Palencia,<sup>17</sup> V. Papadimitriou,<sup>17</sup> A. Papaikonomou,<sup>26</sup> A. A. Paramonov,<sup>13</sup> B. Parks,<sup>38</sup> S. Pashapour,<sup>33</sup> J. Patrick,<sup>17</sup> G. Pauletta,<sup>53</sup> M. Paulini,<sup>12</sup> C. Paus,<sup>32</sup> D. E. Pellett,<sup>7</sup> A. Penzo,<sup>53</sup> T. J. Phillips,<sup>16</sup> G. Piacentino,<sup>45</sup> J. Piedra,<sup>43</sup> L. Pinera,<sup>18</sup> K. Pitts,<sup>24</sup> C. Plager,<sup>8</sup> L. Pondrom,<sup>58</sup> X. Portell,<sup>3</sup> O. Poukhov,<sup>15</sup> N. Pounder,<sup>41</sup> F. Prakoshyn,<sup>15</sup> A. Pronko,<sup>17</sup> J. Proudfoot,<sup>2</sup> F. Ptohos,<sup>17,h</sup> G. Punzi,<sup>45</sup> J. Pursley,<sup>58</sup> J. Rademacker,<sup>41,c</sup> A. Rahaman,<sup>46</sup> V. Ramakrishnan,<sup>58</sup> N. Ranjan,<sup>47</sup> I. Redondo,<sup>31</sup> B. Reiser,<sup>17</sup> V. Rekovic,<sup>36</sup> P. Renton,<sup>41</sup> M. Rescigno,<sup>50</sup> S. Richter,<sup>26</sup> F. Rimondi,<sup>5</sup> L. Ristori,<sup>45</sup> A. Robson,<sup>21</sup> T. Rodrigo,<sup>11</sup> E. Rogers,<sup>24</sup> S. Rolli,<sup>55</sup> R. Roser,<sup>17</sup> M. Rossi,<sup>53</sup> R. Rossin,<sup>10</sup> P. Roy,<sup>33</sup> A. Ruiz,<sup>11</sup> J. Russ,<sup>12</sup> V. Rusu,<sup>17</sup> H. Saarikko,<sup>23</sup> A. Safonov,<sup>52</sup> W. K. Sakumoto,<sup>48</sup> G. Salamanna,<sup>50</sup> O. Saltó,<sup>3</sup> L. Santi,<sup>53</sup> S. Sarkar,<sup>50</sup> L. Sartori,<sup>45</sup> K. Sato,<sup>17</sup> P. Savard,<sup>33</sup> A. Savoy-Navarro,<sup>43</sup> T. Scheidle,<sup>26</sup> P. Schlabach,<sup>17</sup> E. E. Schmidt,<sup>17</sup> M. A. Schmidt,<sup>13</sup> M. P. Schmidt,<sup>59</sup> M. Schmitt,<sup>37</sup> T. Schwarz,<sup>7</sup> L. Scodellaro,<sup>11</sup> A. L. Scott,<sup>10</sup> A. Scribano,<sup>45</sup> F. Scuri,<sup>45</sup> A. Sedov,<sup>47</sup> S. Seidel,<sup>36</sup> Y. Seiya,<sup>40</sup> A. Semenov,<sup>15</sup> L. Sexton-Kennedy,<sup>17</sup> A. Sfyrla,<sup>20</sup> S. Z. Shalhout,<sup>57</sup> M. D. Shapiro,<sup>28</sup> T. Shears,<sup>29</sup> P. F. Shepard,<sup>46</sup> D. Sherman,<sup>22</sup> M. Shimojima,<sup>54,n</sup> M. Shochet,<sup>13</sup> Y. Shon,<sup>58</sup> I. Shreyber,<sup>20</sup> A. Sidoti,<sup>45</sup> P. Sinervo,<sup>33</sup> A. Sisakyan,<sup>15</sup> A. J. Slaughter,<sup>17</sup> J. Slaunwhite,<sup>38</sup> K. Sliwa,<sup>55</sup> J. R. Smith,<sup>7</sup> F. D. Snider,<sup>17</sup> R. Snihur,<sup>33</sup> M. Soderberg,<sup>34</sup> A. Soha,<sup>7</sup> S. Somalwar,<sup>51</sup> V. Sorin,<sup>35</sup> J. Spalding,<sup>17</sup> F. Spinella,<sup>45</sup> T. Spreitzer,<sup>33</sup> P. Squillacioti,<sup>45</sup> M. Stanitzki,<sup>59</sup> R. St. Denis,<sup>21</sup> B. Stelzer,<sup>8</sup> O. Stelzer-Chilton,<sup>41</sup> D. Stentz,<sup>37</sup> J. Strologas,<sup>36</sup> D. Stuart,<sup>10</sup> J. S. Suh,<sup>27</sup> A. Sukhanov,<sup>18</sup> H. Sun,<sup>55</sup> I. Suslov,<sup>15</sup> T. Suzuki,<sup>54</sup> A. Taffard,<sup>24,e</sup> R. Takashima,<sup>39</sup> Y. Takeuchi,<sup>54</sup> R. Tanaka,<sup>39</sup> M. Tecchio,<sup>34</sup> P. K. Teng,<sup>1</sup> K. Terashi,<sup>49</sup> J. Thom,<sup>17,g</sup> A. S. Thompson,<sup>21</sup> G. A. Thompson,<sup>24</sup> E. Thomson,<sup>44</sup> P. Tipton,<sup>59</sup> V. Tiwari,<sup>12</sup> S. Tkaczyk,<sup>17</sup> D. Toback,<sup>52</sup> S. Tokar,<sup>14</sup> K. Tollefson,<sup>35</sup> T. Tomura,<sup>54</sup> D. Tonelli,<sup>17</sup> S. Torre,<sup>19</sup> D. Torretta,<sup>17</sup> S. Tournear,<sup>43</sup> W. Trischuk,<sup>33</sup> Y. Tu,<sup>44</sup> N. Turini,<sup>45</sup> F. Ukegawa,<sup>54</sup> S. Uozumi,<sup>54</sup> S. Vallecorsa,<sup>20</sup> N. van Remortel,<sup>23</sup> A. Varganov,<sup>34</sup> E. Vataga,<sup>36</sup> F. Vázquez,<sup>18,l</sup> G. Velez,<sup>17</sup> C. Vellidis,<sup>45,a</sup> V. Veszpremi,<sup>47</sup> M. Vidal,<sup>31</sup> R. Vidal,<sup>17</sup> I. Vila,<sup>11</sup> R. Vilar,<sup>11</sup> T. Vine,<sup>30</sup> M. Vogel,<sup>36</sup> I. Volobouev,<sup>28,q</sup> G. Volpi,<sup>45</sup> F. Würthwein,<sup>9</sup> P. Wagner,<sup>44</sup> R. G. Wagner,<sup>2</sup> R. L. Wagner,<sup>17</sup> J. Wagner,<sup>26</sup> W. Wagner,<sup>26</sup> T. Wakisaka,<sup>40</sup> R. Wallny,<sup>8</sup> S. M. Wang,<sup>1</sup> A. Warburton,<sup>33</sup> D. Waters,<sup>30</sup> M. Weinberger,<sup>52</sup> W. C. Wester III,<sup>17</sup> B. Whitehouse,<sup>55</sup> D. Whiteson,<sup>44,e</sup> A. B. Wicklund,<sup>2</sup> E. Wicklund,<sup>17</sup> G. Williams,<sup>33</sup> H. H. Williams,<sup>44</sup> P. Wilson,<sup>17</sup> B. L. Winer,<sup>38</sup> P. Wittich,<sup>17,g</sup> S. Wolbers,<sup>17</sup> C. Wolfe,<sup>13</sup> T. Wright,<sup>34</sup> X. Wu,<sup>20</sup> S. M. Wynne,<sup>29</sup> A. Yagil,<sup>9</sup> K. Yamamoto,<sup>40</sup> J. Yamaoka,<sup>51</sup> T. Yamashita,<sup>39</sup> C. Yang,<sup>59</sup> U. K. Yang,<sup>13,m</sup> Y. C. Yang,<sup>27</sup> W. M. Yao,<sup>28</sup> G. P. Yeh,<sup>17</sup> J. Yoh,<sup>17</sup> K. Yorita,<sup>13</sup> T. Yoshida,<sup>40</sup> G. B. Yu,<sup>48</sup> I. Yu,<sup>27</sup> S. S. Yu,<sup>17</sup> J. C. Yun,<sup>17</sup> L. Zanello,<sup>50</sup> A. Zanetti,<sup>53</sup> I. Zaw,<sup>22</sup> X. Zhang,<sup>24</sup> Y. Zheng,<sup>8,b</sup> and S. Zucchelli<sup>5</sup>

(CDF Collaboration)

<sup>1</sup>*Institute of Physics, Academia Sinica, Taipei, Taiwan 11529, Republic of China*<sup>2</sup>*Argonne National Laboratory, Argonne, Illinois 60439, USA*<sup>3</sup>*Institut de Física d'Altes Energies, Universitat Autònoma de Barcelona, E-08193, Bellaterra (Barcelona), Spain*<sup>4</sup>*Baylor University, Waco, Texas 76798, USA*<sup>5</sup>*Istituto Nazionale di Fisica Nucleare, University of Bologna, I-40127 Bologna, Italy*<sup>6</sup>*Brandeis University, Waltham, Massachusetts 02254, USA*<sup>7</sup>*University of California, Davis, Davis, California 95616, USA*<sup>8</sup>*University of California, Los Angeles, Los Angeles, California 90024, USA*<sup>9</sup>*University of California, San Diego, La Jolla, California 92093, USA*<sup>10</sup>*University of California, Santa Barbara, Santa Barbara, California 93106, USA*<sup>11</sup>*Instituto de Física de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain*<sup>12</sup>*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*<sup>13</sup>*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA*<sup>14</sup>*Comenius University, 842 48 Bratislava, Slovakia; Institute of Experimental Physics, 040 01 Kosice, Slovakia*<sup>15</sup>*Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*<sup>16</sup>*Duke University, Durham, North Carolina 27708*<sup>17</sup>*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*<sup>18</sup>*University of Florida, Gainesville, Florida 32611, USA*<sup>19</sup>*Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*<sup>20</sup>*University of Geneva, CH-1211 Geneva 4, Switzerland*<sup>21</sup>*Glasgow University, Glasgow G12 8QQ, United Kingdom*<sup>22</sup>*Harvard University, Cambridge, Massachusetts 02138, USA*<sup>23</sup>*Division of High Energy Physics, Department of Physics, University of Helsinki and Helsinki Institute of Physics, FIN-00014, Helsinki, Finland*<sup>24</sup>*University of Illinois, Urbana, Illinois 61801, USA*

- <sup>25</sup>The Johns Hopkins University, Baltimore, Maryland 21218, USA  
<sup>26</sup>Institut für Experimentelle Kernphysik, Universität Karlsruhe, 76128 Karlsruhe, Germany  
<sup>27</sup>Center for High Energy Physics: Kyungpook National University, Daegu 702-701, Korea;  
 Seoul National University, Seoul 151-742, Korea;  
 SungKyunKwan University, Suwon 440-746, Korea;  
 Korea Institute of Science and Technology Information, Daejeon, 305-806, Korea;  
 Chonnam National University, Gwangju, 500-757, Korea  
<sup>28</sup>Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA  
<sup>29</sup>University of Liverpool, Liverpool L69 7ZE, United Kingdom  
<sup>30</sup>University College London, London WC1E 6BT, United Kingdom  
<sup>31</sup>Centro de Investigaciones Energeticas Medioambientales y Tecnologicas, E-28040 Madrid, Spain  
<sup>32</sup>Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA  
<sup>33</sup>Institute of Particle Physics: McGill University, Montréal, Canada H3A 2T8;  
 and University of Toronto, Toronto, Canada M5S 1A7  
<sup>34</sup>University of Michigan, Ann Arbor, Michigan 48109, USA  
<sup>35</sup>Michigan State University, East Lansing, Michigan 48824, USA  
<sup>36</sup>University of New Mexico, Albuquerque, New Mexico 87131, USA  
<sup>37</sup>Northwestern University, Evanston, Illinois 60208, USA  
<sup>38</sup>The Ohio State University, Columbus, Ohio 43210, USA  
<sup>39</sup>Okayama University, Okayama 700-8530, Japan  
<sup>40</sup>Osaka City University, Osaka 588, Japan  
<sup>41</sup>University of Oxford, Oxford OX1 3RH, United Kingdom  
<sup>42</sup>University of Padova, Istituto Nazionale di Fisica Nucleare, Sezione di Padova-Trento, I-35131 Padova, Italy  
<sup>43</sup>LPNHE, Universite Pierre et Marie Curie/IN2P3-CNRS, UMR7585, Paris, F-75252 France  
<sup>44</sup>University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA  
<sup>45</sup>Istituto Nazionale di Fisica Nucleare Pisa, Universities of Pisa, Siena and Scuola Normale Superiore, I-56127 Pisa, Italy  
<sup>46</sup>University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA  
<sup>47</sup>Purdue University, West Lafayette, Indiana 47907, USA  
<sup>48</sup>University of Rochester, Rochester, New York 14627, USA  
<sup>49</sup>The Rockefeller University, New York, New York 10021, USA  
<sup>50</sup>Istituto Nazionale di Fisica Nucleare, Sezione di Roma 1, University of Rome “La Sapienza,” I-00185 Roma, Italy  
<sup>51</sup>Rutgers University, Piscataway, New Jersey 08855, USA  
<sup>52</sup>Texas A&M University, College Station, Texas 77843, USA  
<sup>53</sup>Istituto Nazionale di Fisica Nucleare, University of Trieste/Udine, Italy  
<sup>54</sup>University of Tsukuba, Tsukuba, Ibaraki 305, Japan  
<sup>55</sup>Tufts University, Medford, Massachusetts 02155, USA  
<sup>56</sup>Waseda University, Tokyo 169, Japan  
<sup>57</sup>Wayne State University, Detroit, Michigan 48201, USA  
<sup>58</sup>University of Wisconsin, Madison, Wisconsin 53706, USA  
<sup>59</sup>Yale University, New Haven, Connecticut 06520, USA  
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We report the observation of two narrow resonances consistent with states of orbitally excited ( $L = 1$ )  $B_s$  mesons using  $1 \text{ fb}^{-1}$  of  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96 \text{ TeV}$  collected with the Collider Detector at Fermilab II detector at the Fermilab Tevatron. We use two-body decays into  $K^-$  and  $B^+$  mesons reconstructed as  $B^+ \rightarrow J/\psi K^+$ ,  $J/\psi \rightarrow \mu^+ \mu^-$  or  $B^+ \rightarrow \bar{D}^0 \pi^+$ ,  $\bar{D}^0 \rightarrow K^+ \pi^-$ . We deduce the masses of the two states to be  $m(B_{s1}) = 5829.4 \pm 0.7 \text{ MeV}/c^2$  and  $m(B_{s2}^*) = 5839.6 \pm 0.7 \text{ MeV}/c^2$ .

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The heavy mesons consisting of a light and a heavy quark form an interesting laboratory for the study of QCD, the theory of the strong interaction. They are a close analogue to the hydrogen atom and play a similar role for the study of the QCD as hydrogen for quantum electrodynamics. According to heavy quark effective theory (HQET) [1], in the limit of infinite mass of the heavy quark, the heavy quark decouples from the degrees of freedom of the light quark. For orbitally excited states ( $L = 1$ ), the total angular momentum of the light quark

is  $j_q = 1/2$  or  $j_q = 3/2$ . Combining  $j_q$  with the spin of the heavy quark, four states forming two  $j_q$  doublets are expected. For an infinite mass of heavy quark, the four states are degenerate in mass. However, corrections due to finite mass lead to fine structure splitting between the two doublets and hyperfine structure splitting within each of the doublets. Following the standard scheme [2], the states with  $j_q = 1/2$  are named  $B_{s0}^*$  and  $B_{s1}$ , and the states with  $j_q = 3/2$  are named  $B_{s1}$  and  $B_{s2}^*$ . Often these four states are referred to as  $B_s^{**}$ .

If kinematically allowed, all four  $B_s^{**}$  states are expected to decay dominantly to  $B^*K$ ,  $BK$  or both. The states of the doublet with  $j_q = 1/2$  decay through an  $S$ -wave transition and are therefore expected to have broad mass distributions. The states with  $j_q = 3/2$  decay through a  $D$ -wave transition and therefore are expected to have narrow mass distributions. In the following we focus on the narrow doublet. While the  $B_{s1}$  decays only into  $B^*K$  due to conservation of spin and parity, the  $B_{s2}^*$  can decay to  $B^*K$  and  $BK$ . If the  $B_{s2}^*$  mass is near the  $B^*K$  threshold, the decay to  $B^*K$  will be strongly suppressed compared to the decay to  $BK$  due to the available phase space.

Several theoretical predictions for the basic properties of the  $B_s^{**}$  states are available [3]. The predictions for the  $B_{s1}$  mass range from 5805 to 5891 MeV/ $c^2$ , and for  $B_{s2}^*$  5820 to 5903 MeV/ $c^2$  with a mass difference between both states in the range 12 to 20 MeV/ $c^2$ . The natural widths of the two states are expected to be of order 1 MeV/ $c^2$  with strong variation with predicted mass.

While there is already considerable information about  $D_s^{**}$  mesons, the analogous particles in the charm sector [2,4], experimental knowledge about the  $B_s^{**}$  mesons is minimal. First evidence for at least one of the  $B_s^{**}$  states was found by the OPAL experiment [5]. Evidence for a single state interpreted as  $B_{s2}^*$  was seen by the Delphi Collaboration [6] and a preliminary observation of this state was reported recently by the D0 Collaboration [7].

In this Letter, we report on the observation of two states consistent with the  $j_q = 3/2$  doublet of the  $B_s^{**}$  decaying to  $B^+K^-$  and  $B^{*+}K^-$  with  $B^{*+} \rightarrow B^+\gamma$ , where the photon is not detected. Because of the missing photon, the observed  $B_{s1}$  peak is shifted downward in mass by the  $B^*-B$  mass splitting of  $45.78 \pm 0.35$  MeV/ $c^2$  [2].  $B^+$  mesons are reconstructed in two decay channels,  $B^+ \rightarrow J/\psi K^+$  with  $J/\psi \rightarrow \mu^+\mu^-$  and  $B^+ \rightarrow \bar{D}^0\pi^+$  with  $\bar{D}^0 \rightarrow K^+\pi^-$ . The use of a specific particle state implies the use of the charge-conjugate state as well. We use data collected by the Collider Detector at Fermilab II (CDF II) at the Tevatron between February 2002 and February 2006 corresponding to a total integrated luminosity of 1 fb $^{-1}$ .

The components of the CDF II detector [8] used for this analysis are the magnetic spectrometer and the muon detectors. The tracking system is composed of a silicon microstrip detector [9] surrounded by an open-cell drift chamber (COT) [10]. Both components are located inside a 1.4 T axial magnetic field. Muons are detected in planes of multiwire drift chambers and scintillators [11] in the pseudorapidity range  $|\eta| \leq 1.0$ , where  $\eta = -\ln \tan(\theta/2)$  and  $\theta$  is the polar angle measured from the proton beam direction. Hadron identification is crucial for distinguishing kaons originating from  $B_s^{**}$  decays from other particles. It is provided by a combination of the ionization energy loss in the COT and a measurement by a time-of-flight system [12].

A three-level trigger system is used for the online event selection. The level 1 trigger system includes the eXtremely Fast Tracker (XFT) processor [13] which finds charged-particle tracks in the COT and measures their azimuthal angle around the beam direction and transverse momenta. In level 2, the silicon vertex trigger [14] adds hits from the silicon detector to tracks found by the XFT to provide measurements of impact parameter. The level 3 system confirms the selections using a version of the offline event reconstruction optimized for speed.

The dimuon trigger [8] requires two tracks of opposite charge matched to track segments in the muon chambers, where the mass of the pair is consistent with the  $J/\psi$  mass. The displaced-vertex trigger [15] requires two tracks with large impact parameters. Additionally, the intersection of the tracks has to be displaced from the interaction point and a minimum transverse momentum, the momentum component perpendicular to the proton beam direction, is required for each track.

In both samples, we reconstruct  $B_s^{**}$  candidates by combining  $B^+$  candidates with  $K^-$  candidates. In the dimuon (displaced-vertex) trigger sample, we form  $J/\psi \rightarrow \mu^+\mu^-$  ( $\bar{D}^0 \rightarrow K^+\pi^-$ ) candidates and combine each  $J/\psi$  ( $\bar{D}^0$ ) candidate with a track assumed to be a kaon (pion), constraining the tracks to an appropriate decay topology to form a  $B^+$  candidate. At this stage hadron identification is not used. In order to improve the mass resolution, we consider the quantity  $Q$  defined as  $m(B^+K^-) - m(B^+) - M_{K^-}$ , where  $m(B^+K^-)$  and  $m(B^+)$  are the reconstructed invariant masses of the  $B^+K^-$  pair and the  $B^+$  candidate, and  $M_{K^-}$  is the known kaon mass [2]. The predicted  $B_{s1}$  ( $B_{s2}^*$ ) state mass translates to the region  $0 < Q < 73$  MeV/ $c^2$  ( $48 < Q < 131$  MeV/ $c^2$ ).

For the selection of candidates, we use a chain of two neural networks based on the NEUROBAYES [16] package in each of the  $B^+$  decay channels. In a first step, a neural network in each channel combines topological, kinematic, and particle identification quantities for the  $B^+$  and its daughters to form a single discriminant between  $B^+$  mesons and background. The most important quantities are the impact parameter of the  $B^+$ , the projection of the displacement of its reconstructed decay point from the beam line on the direction of its transverse momentum, the transverse momentum of the  $B^+$  decay's pion (kaon), and its impact parameter. The neural networks are trained on two classes of events corresponding to the signal and background samples. In the  $B^+ \rightarrow J/\psi K^+$  channel, we use a PYTHIA [17] simulation for the signal sample and experimental data from the  $B^+$  mass sidebands 5190–5240 MeV/ $c^2$  and 5320–5395 MeV/ $c^2$  for the background sample. In the  $B^+ \rightarrow \bar{D}^0\pi^+$  channel we use only experimental data to train the  $B^+$  neural network. We use candidates from a signal region between 5240 and 5310 MeV/ $c^2$  in the invariant mass as signal sample and data from a  $B^+$  mass sideband between 5325 and

5370 MeV/ $c^2$  as background sample. The events from the  $B^+$  mass sidebands are used also as signal with negative weight to account for the background in the signal region. Based on the neural networks, we select approximately 31 000  $B^+$  signal events in the  $J/\psi K^+$  decay channel and 27 200 in the  $\bar{D}^0 \pi^+$  channel.

In a second step, we select  $B_s^{**}$  candidates based on the number of candidates per event and on an additional neural network for each  $B^+$  decay channel. These neural networks use the same inputs as used by the neural networks to select  $B^+$  mesons as well as their discriminant, and kinematic and particle identification quantities for the kaon track of the  $B_s^{**}$  decay. The particle identification of the kaon is the most important variable, followed by the neural network discriminant of the  $B^+$  and the pseudorapidity of the kaon. The number of candidates per event is not used in the neural network due to the difficulty of modeling fragmentation and hadronization in the production of heavy quarks. We select only those events with fewer than four candidates because a lower number of candidates provides a better signal-to-background ratio. This cut is fixed without looking to the experimental data, based only upon the above assumption. The  $B_s^{**}$  neural networks are trained on a combination of simulated events, containing only signal, and data events in the  $Q$  range 0–200 MeV/ $c^2$  for background sample. The number of real  $B_s^{**}$  mesons in the background-training sample is too small to affect significantly the learning process of the neural network. In order to avoid possible mass biases, the simulated signal events have the same  $B^+ K^-$  mass distribution as the events used for background in the neural network training. The value of the cut on the neural network discriminant for the final selection is chosen to optimize  $N_{MC}/\sqrt{N_{data}}$ , where  $N_{data}$  ( $N_{MC}$ ) is the number of the selected candidates in data (simulation) in the  $Q$  range 60–70 MeV/ $c^2$ . This range has been chosen based on the mass of the previously seen  $B_{s2}^*$  state and therefore is not biased with respect to the unobserved state. We verify that the observed  $B_s^{**}$  masses do not depend on the  $Q$  range used for cut optimization. The  $Q$  distributions of the selected candidates are shown in Figs. 1(a) and 1(b) for the two trigger samples separately, and in Fig. 1(c) added together. Two peaks are visible, centered near 67 MeV/ $c^2$  and near 10 MeV/ $c^2$ . The wrong-sign combinations (filled area in Fig. 1) do not show any significant structure.

The two peaks in data can be interpreted as the two  $j_q = 3/2$  states of orbitally excited  $B_s$  mesons. The natural interpretation is that the peak near 67 MeV/ $c^2$  stems from the  $B_{s2}^* \rightarrow B^+ K^-$  decay while the peak near 10 MeV/ $c^2$  stems from the decay  $B_{s1}^* \rightarrow B^{*+} K^-$ . Reversing the assignment of the two peaks would result in a larger mass difference between  $B_{s2}^*$  and  $B_{s1}^*$  with  $B_{s1}^*$  being heavier, which would be opposite to other heavy quark mesons.

To extract the mean  $Q$  values for the two peaks, we use an unbinned maximum likelihood fit. Each of the peaks is

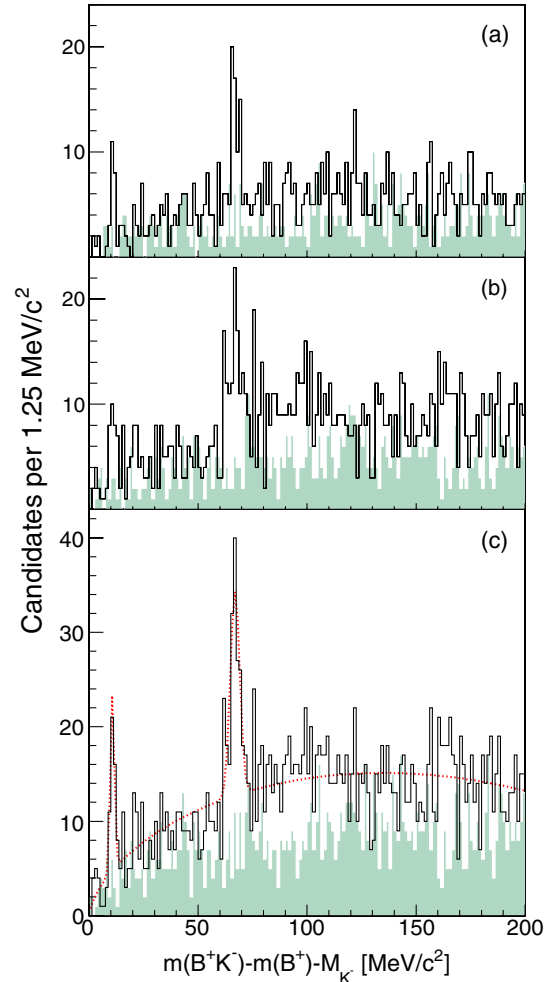


FIG. 1 (color online). Distribution of  $Q = m(B^+ K^-) - m(B^+) - M_K$  for the  $B_s^{**}$  candidates with (a)  $B^+ \rightarrow J/\psi K^+$ , (b)  $B^+ \rightarrow \bar{D}^0 \pi^+$  and (c) both  $B^+$  channels combined. The dotted line shows the result of a fit with the sum of a background function and two Gaussians. The filled area shows the  $Q$  distribution for the wrong-sign combination  $B^+ K^+$ .

described by a Gaussian shape. We use a phenomenological function to describe the background without distinguishing different types of backgrounds. The functional form of the background shape is  $[Q(\beta - Q)]^\gamma \exp(-\gamma Q)$ , where  $\beta$  and  $\gamma$  are free parameters. The fit has three free parameters for each of the Gaussians and two free parameters for the background. The fit to each data sample separately gives results consistent between the two  $B^+$  decay channels. Therefore, we combine the  $B^+$  channels to perform the final fit. The projection of the fit on the full sample is shown in Fig. 1(c). From the fit we extract  $Q(B_{s1}^*) = 10.73 \pm 0.21$  MeV/ $c^2$  and  $Q(B_{s2}^*) = 66.96 \pm 0.39$  MeV/ $c^2$ , with yields  $N(B_{s1}^*) = 36 \pm 9$  events and  $N(B_{s2}^*) = 95 \pm 23$  events, where all uncertainties are statistical. The widths of the Gaussians are consistent with expected detector resolutions.



Systematic uncertainties on the  $Q$  value may arise from the tracking and fitting procedures. The sources of uncertainty from the tracking are the uncertainty on the track error matrix, which enters through vertex fits, and the uncertainty on the material and magnetic field distribution inside the tracking volume. Based on a detailed study performed for the measurement of mass and width of the orbitally excited  $D^{**}$  states [18], we assign a combined systematic uncertainty of  $0.14 \text{ MeV}/c^2$  due to the tracking effects. We study effects on the fitting procedure of the unknown background shape and the simplification by the single-Gaussian signal description. In both cases we generate a large number of samples of the same size as the data. For the background shape study we use a probability density function proportional to a fit on data with a third order polynomial as background function instead of the default one for sample generation. In the signal shape study the sum of two Gaussians, which have the width one gets by fitting each decay channel separately, is used for sample generation. Each of the samples is then fitted using the default fit model and the pull distributions are examined. In both cases the pull distributions are consistent with a Gaussian with a mean of zero and unit width. Therefore, we do not assign any systematic uncertainty arising from the fitting procedure. The resulting  $Q$  values are

$$Q(B_{s1}) = 10.73 \pm 0.21(\text{stat}) \pm 0.14(\text{syst}) \text{ MeV}/c^2,$$

$$Q(B_{s2}^*) = 66.96 \pm 0.39(\text{stat}) \pm 0.14(\text{syst}) \text{ MeV}/c^2.$$

By adding the known values [2] of  $M_{B^*}$  and  $M_{K^-}$  to  $Q(B_{s1})$  and  $M_{B^+}$  with  $M_{K^-}$  to  $Q(B_{s2}^*)$ , we obtain  $m(B_{s1}) = 5829.4 \pm 0.7 \text{ MeV}/c^2$  and  $m(B_{s2}^*) = 5839.6 \pm 0.7 \text{ MeV}/c^2$ . The statistical and systematic uncertainties on the  $Q$  value and the uncertainties on the masses of  $K^-$  and  $B^+$  or  $B^{*+}$  are added in quadrature. Finally, the mass difference of the two narrow  $B_s^{**}$  states is  $\Delta m(B_{s2}^*, B_{s1}) = 10.5 \pm 0.6 \text{ MeV}/c^2$ , where we add  $M_{B^*} - M_B = 45.78 \pm 0.35 \text{ MeV}/c^2$  to the difference of the two measured  $Q$  values.

To estimate the statistical significance of each of the two peaks, we repeat the fit without the term for one of the Gaussian peaks and again without the other peak. For each peak we form  $\Delta\mathcal{L} = -2 \ln \mathcal{L}_0 / \mathcal{L}$ , where  $\mathcal{L}$  is the value of the likelihood function of the original fit and  $\mathcal{L}_0$  is the value for the fit without one of the peaks, and measure  $\Delta\mathcal{L} = 48.7$  (74.5) for  $B_{s1}$  ( $B_{s2}^*$ ). We generate samples with background according to the background function from the fit to the data and one of the peaks. For each of the samples, we evaluate  $\Delta\mathcal{L}$ . In the  $\Delta\mathcal{L}$  distribution for samples created without  $B_{s1}$  ( $B_{s2}^*$ ) the highest observed value is 35.2 (41.8) in over 4.6 (5.6) million samples where the peak is located in range 0–50  $\text{MeV}/c^2$  (20–120  $\text{MeV}/c^2$ ). Therefore, we conclude that the statistical significance of each of the signals exceeds 5 standard deviations.

In summary, we report the first observation of the narrow  $j_q = 3/2$  states of the orbitally excited  $B_s$  mesons. The signals observed are attributed to the  $B_{s2}^* \rightarrow B^+ K^-$  and  $B_{s1} \rightarrow B^{*+} K^-$  decays. From the precise measurement of the  $Q$  values, we derive the masses of the two states and their mass difference, and the values are consistent with theoretical predictions [3].

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<sup>a</sup>Visitor from University of Athens, 15784 Athens, Greece.

<sup>b</sup>Visitor from Chinese Academy of Sciences, Beijing 100864, China.

<sup>c</sup>Visitor from University of Bristol, Bristol BS8 1TL, United Kingdom.

<sup>d</sup>Visitor from University Libre de Bruxelles, B-1050 Brussels, Belgium.

<sup>e</sup>Visitor from University of California Irvine, Irvine, CA 92697, USA.

<sup>f</sup>Visitor from University of California Santa Cruz, Santa Cruz, CA 95064, USA.

<sup>g</sup>Visitor from Cornell University, Ithaca, New York 14853, USA.

<sup>h</sup>Visitor from University of Cyprus, Nicosia CY-1678, Cyprus.

<sup>i</sup>Visitor from University College Dublin, Dublin 4, Ireland

<sup>j</sup>Visitor from University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom.

<sup>k</sup>Visitor from University of Heidelberg, D-69120 Heidelberg, Germany.

<sup>l</sup>Visitor from Universidad Iberoamericana, Mexico D.F., Mexico.

<sup>m</sup>Visitor from University of Manchester, Manchester M13 9PL, United Kingdom.

<sup>n</sup>Visitor from Nagasaki Institute of Applied Science, Nagasaki, Japan.

- <sup>o</sup>Visitor from University de Oviedo, E-33007 Oviedo, Spain.
- <sup>p</sup>Visitor from Queen Mary, University of London, London, E1 4NS, United Kingdom.
- <sup>q</sup>Visitor from Texas Tech University, Lubbock, Texas 79409, USA.
- <sup>r</sup>Visitor from IFIC(CSIC-Universitat de Valencia), 46071 Valencia, Spain.
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