

## Production of Prompt Charmonia in $e^+e^-$ Annihilation at $\sqrt{s} \approx 10.6$ GeV

K. Abe,<sup>9</sup> K. Abe,<sup>39</sup> T. Abe,<sup>40</sup> I. Adachi,<sup>9</sup> Byoung Sup Ahn,<sup>16</sup> H. Aihara,<sup>41</sup> M. Akatsu,<sup>21</sup> Y. Asano,<sup>46</sup> T. Aso,<sup>45</sup> T. Aushev,<sup>14</sup> A. M. Bakich,<sup>37</sup> Y. Ban,<sup>32</sup> E. Banas,<sup>26</sup> S. Behari,<sup>9</sup> P. K. Behera,<sup>47</sup> A. Bondar,<sup>2</sup> A. Bozek,<sup>26</sup> T. E. Browder,<sup>8</sup> B. C. K. Casey,<sup>8</sup> P. Chang,<sup>25</sup> Y. Chao,<sup>25</sup> B. G. Cheon,<sup>36</sup> R. Chistov,<sup>14</sup> S.-K. Choi,<sup>7</sup> Y. Choi,<sup>36</sup> L. Y. Dong,<sup>12</sup> J. Dragic,<sup>19</sup> A. Drutskoy,<sup>14</sup> S. Eidelman,<sup>2</sup> Y. Enari,<sup>21</sup> F. Fang,<sup>8</sup> H. Fujii,<sup>9</sup> C. Fukunaga,<sup>43</sup> M. Fukushima,<sup>11</sup> N. Gabyshev,<sup>9</sup> A. Garmash,<sup>2,8</sup> T. Gershon,<sup>9</sup> A. Gordon,<sup>19</sup> R. Guo,<sup>23</sup> J. Haba,<sup>9</sup> H. Hamasaki,<sup>9</sup> F. Handa,<sup>40</sup> K. Hara,<sup>30</sup> T. Hara,<sup>30</sup> H. Hayashii,<sup>22</sup> M. Hazumi,<sup>30</sup> E. M. Heenan,<sup>19</sup> I. Higuchi,<sup>40</sup> T. Hokuue,<sup>21</sup> Y. Hoshi,<sup>39</sup> S. R. Hou,<sup>25</sup> W.-S. Hou,<sup>25</sup> H.-C. Huang,<sup>25</sup> Y. Igarashi,<sup>9</sup> T. Iijima,<sup>9</sup> H. Ikeda,<sup>9</sup> K. Inami,<sup>21</sup> A. Ishikawa,<sup>21</sup> H. Ishino,<sup>42</sup> R. Itoh,<sup>9</sup> H. Iwasaki,<sup>9</sup> Y. Iwasaki,<sup>9</sup> P. Jalocho,<sup>26</sup> H. K. Jang,<sup>35</sup> J. H. Kang,<sup>50</sup> J. S. Kang,<sup>16</sup> P. Kapusta,<sup>26</sup> N. Katayama,<sup>9</sup> H. Kawai,<sup>41</sup> N. Kawamura,<sup>1</sup> T. Kawasaki,<sup>28</sup> H. Kichimi,<sup>9</sup> D. W. Kim,<sup>36</sup> Heejong Kim,<sup>50</sup> H. J. Kim,<sup>50</sup> H. O. Kim,<sup>36</sup> Hyunwoo Kim,<sup>16</sup> S. K. Kim,<sup>35</sup> T. H. Kim,<sup>50</sup> K. Kinoshita,<sup>5</sup> S. Kobayashi,<sup>34</sup> H. Konishi,<sup>44</sup> P. Krokovny,<sup>2</sup> R. Kulasiri,<sup>5</sup> S. Kumar,<sup>31</sup> A. Kuzmin,<sup>2</sup> Y.-J. Kwon,<sup>50</sup> J. S. Lange,<sup>6</sup> G. Leder,<sup>13</sup> S. H. Lee,<sup>35</sup> D. Liventsev,<sup>14</sup> R.-S. Lu,<sup>25</sup> J. MacNaughton,<sup>13</sup> D. Marlow,<sup>33</sup> T. Matsubara,<sup>41</sup> S. Matsumoto,<sup>4</sup> T. Matsumoto,<sup>21</sup> Y. Mikami,<sup>40</sup> K. Miyabayashi,<sup>22</sup> H. Miyake,<sup>30</sup> H. Miyata,<sup>28</sup> G. R. Moloney,<sup>19</sup> S. Mori,<sup>46</sup> T. Mori,<sup>4</sup> T. Nagamine,<sup>40</sup> Y. Nagasaka,<sup>10</sup> Y. Nagashima,<sup>30</sup> E. Nakano,<sup>29</sup> M. Nakao,<sup>9</sup> J. W. Nam,<sup>36</sup> Z. Natkaniec,<sup>26</sup> K. Neichi,<sup>39</sup> S. Nishida,<sup>17</sup> O. Nitoh,<sup>44</sup> S. Noguchi,<sup>22</sup> T. Nozaki,<sup>9</sup> S. Ogawa,<sup>38</sup> T. Ohshima,<sup>21</sup> T. Okabe,<sup>21</sup> S. Okuno,<sup>15</sup> W. Ostrowicz,<sup>26</sup> H. Ozaki,<sup>9</sup> P. Pakhlov,<sup>14</sup> H. Palka,<sup>26</sup> C. S. Park,<sup>35</sup> C. W. Park,<sup>16</sup> H. Park,<sup>18</sup> K. S. Park,<sup>36</sup> M. Peters,<sup>8</sup> L. E. Pilonen,<sup>48</sup> N. Root,<sup>2</sup> K. Rybicki,<sup>26</sup> J. Ryuko,<sup>30</sup> H. Sagawa,<sup>9</sup> Y. Sakai,<sup>9</sup> H. Sakamoto,<sup>17</sup> M. Satapathy,<sup>47</sup> A. Satpathy,<sup>9,5</sup> S. Schrenk,<sup>5</sup> S. Semenov,<sup>14</sup> K. Senyo,<sup>21</sup> M. E. Sevier,<sup>19</sup> H. Shibuya,<sup>38</sup> B. Shwartz,<sup>2</sup> S. Stanič,<sup>46</sup> A. Sugi,<sup>21</sup> A. Sugiyama,<sup>21</sup> K. Sumisawa,<sup>9</sup> T. Sumiyoshi,<sup>9</sup> J.-I. Suzuki,<sup>9</sup> K. Suzuki,<sup>3</sup> S. Suzuki,<sup>49</sup> S. K. Swain,<sup>8</sup> T. Takahashi,<sup>29</sup> F. Takasaki,<sup>9</sup> M. Takita,<sup>30</sup> K. Tamai,<sup>9</sup> N. Tamura,<sup>28</sup> J. Tanaka,<sup>41</sup> M. Tanaka,<sup>9</sup> Y. Tanaka,<sup>20</sup> G. N. Taylor,<sup>19</sup> Y. Teramoto,<sup>29</sup> M. Tomoto,<sup>9</sup> T. Tomura,<sup>41</sup> S. N. Tovey,<sup>19</sup> K. Trabelsi,<sup>8</sup> W. Trischuk,<sup>33,\*</sup> T. Tsuboyama,<sup>9</sup> T. Tsukamoto,<sup>9</sup> S. Uehara,<sup>9</sup> K. Ueno,<sup>25</sup> Y. Unno,<sup>3</sup> S. Uno,<sup>9</sup> Y. Ushiroda,<sup>9</sup> S. E. Vahsen,<sup>33</sup> K. E. Varvell,<sup>37</sup> C. C. Wang,<sup>25</sup> C. H. Wang,<sup>24</sup> J. G. Wang,<sup>48</sup> M.-Z. Wang,<sup>25</sup> Y. Watanabe,<sup>42</sup> E. Won,<sup>35</sup> B. D. Yabsley,<sup>9</sup> Y. Yamada,<sup>9</sup> M. Yamaga,<sup>40</sup> A. Yamaguchi,<sup>40</sup> Y. Yamashita,<sup>27</sup> M. Yamauchi,<sup>9</sup> K. Yoshida,<sup>21</sup> Y. Yuan,<sup>12</sup> Y. Yusa,<sup>40</sup> C. C. Zhang,<sup>12</sup> J. Zhang,<sup>46</sup> H. W. Zhao,<sup>9</sup> Y. Zheng,<sup>8</sup> V. Zhilich,<sup>2</sup> and D. Žontar<sup>46</sup>

(Belle Collaboration)

<sup>1</sup>Aomori University, Aomori

<sup>2</sup>Budker Institute of Nuclear Physics, Novosibirsk

<sup>3</sup>Chiba University, Chiba

<sup>4</sup>Chuo University, Tokyo

<sup>5</sup>University of Cincinnati, Cincinnati, Ohio

<sup>6</sup>University of Frankfurt, Frankfurt

<sup>7</sup>Gyeongsang National University, Chinju

<sup>8</sup>University of Hawaii, Honolulu, Hawaii

<sup>9</sup>High Energy Accelerator Research Organization (KEK), Tsukuba

<sup>10</sup>Hiroshima Institute of Technology, Hiroshima

<sup>11</sup>Institute for Cosmic Ray Research, University of Tokyo, Tokyo

<sup>12</sup>Institute of High Energy Physics, Chinese Academy of Sciences, Beijing

<sup>13</sup>Institute of High Energy Physics, Vienna

<sup>14</sup>Institute for Theoretical and Experimental Physics, Moscow

<sup>15</sup>Kanagawa University, Yokohama

<sup>16</sup>Korea University, Seoul

<sup>17</sup>Kyoto University, Kyoto

<sup>18</sup>Kyungpook National University, Taegu

<sup>19</sup>University of Melbourne, Victoria

<sup>20</sup>Nagasaki Institute of Applied Science, Nagasaki

<sup>21</sup>Nagoya University, Nagoya

<sup>22</sup>Nara Women's University, Nara

<sup>23</sup>National Kaohsiung Normal University, Kaohsiung

<sup>24</sup>National Lien-Ho Institute of Technology, Miao Li

<sup>25</sup>National Taiwan University, Taipei

<sup>26</sup>H. Niewodniczanski Institute of Nuclear Physics, Krakow

<sup>27</sup>Nihon Dental College, Niigata

- <sup>28</sup>Niigata University, Niigata  
<sup>29</sup>Osaka City University, Osaka  
<sup>30</sup>Osaka University, Osaka  
<sup>31</sup>Panjab University, Chandigarh  
<sup>32</sup>Peking University, Beijing  
<sup>33</sup>Princeton University, Princeton, New Jersey  
<sup>34</sup>Saga University, Saga  
<sup>35</sup>Seoul National University, Seoul  
<sup>36</sup>Sungkyunkwan University, Suwon  
<sup>37</sup>University of Sydney, Sydney, New South Wales  
<sup>38</sup>Toho University, Funabashi  
<sup>39</sup>Tohoku Gakuin University, Tagajo  
<sup>40</sup>Tohoku University, Sendai  
<sup>41</sup>University of Tokyo, Tokyo  
<sup>42</sup>Tokyo Institute of Technology, Tokyo  
<sup>43</sup>Tokyo Metropolitan University, Tokyo  
<sup>44</sup>Tokyo University of Agriculture and Technology, Tokyo  
<sup>45</sup>Toyama National College of Maritime Technology, Toyama  
<sup>46</sup>University of Tsukuba, Tsukuba  
<sup>47</sup>Utkal University, Bhubaneswer  
<sup>48</sup>Virginia Polytechnic Institute and State University, Blacksburg, Virginia  
<sup>49</sup>Yokkaichi University, Yokkaichi  
<sup>50</sup>Yonsei University, Seoul

(Received 5 October 2001; published 16 January 2002)

The production of prompt  $J/\psi$ ,  $\psi(2S)$ ,  $\chi_{c1}$ , and  $\chi_{c2}$  is studied using a  $32.4 \text{ fb}^{-1}$  data sample collected with the Belle detector at  $Y(4S)$  and at 60 MeV below the resonance. The yield of prompt  $J/\psi$  mesons in the  $Y(4S)$  sample is compatible with that of continuum production; we set an upper limit  $\mathcal{B}(Y(4S) \rightarrow J/\psi X) < 1.9 \times 10^{-4}$  at the 95% confidence level, and find  $\sigma(e^+e^- \rightarrow J/\psi X) = 1.47 \pm 0.10 \pm 0.13 \text{ pb}$ . The cross sections for prompt  $\psi(2S)$  and direct  $J/\psi$  are measured. The  $J/\psi$  momentum spectrum, production angle distribution, and polarization are studied.

DOI: 10.1103/PhysRevLett.88.052001

PACS numbers: 13.65.+i, 13.25.Gv, 14.40.Gx

The production of prompt charmonia is poorly understood, and provides an interesting environment to study the interplay between perturbative QCD and nonperturbative effects. A recently developed effective field theory, called nonrelativistic QCD (NRQCD) [1], provides a consistent calculational framework for direct heavy quarkonium production. Further experimental information is needed to establish the applicability of NRQCD to charmonium production [2]. Studies of prompt charmonia in  $e^+e^-$  collisions at the  $Y(4S)$  resonance constitute a test of NRQCD and can provide estimates of some of its nonperturbative matrix elements.

In this Letter, we report results of a measurement of prompt charmonium production in data recorded at the  $Y(4S)$  and in the continuum 60 MeV below the resonance, corresponding to integrated luminosities of 29.4 and  $3.0 \text{ fb}^{-1}$ , respectively. The data were collected with the Belle detector at the KEKB asymmetric energy ( $3.5 \times 8 \text{ GeV}$ )  $e^+e^-$  storage ring [3].

The Belle detector is a large solid-angle spectrometer equipped with a 1.5 T superconducting solenoid magnet. Charged tracks are reconstructed in a 50 layer central drift chamber (CDC) and in three concentric layers of double sided silicon strip detectors. Photons and electrons are identified using a CsI(Tl) electromagnetic calorimeter

(ECL) located inside the magnet coil. Muons and  $K_L^0$  mesons are detected using resistive plate chambers embedded in the iron magnetic flux return (KLM). Charged particles are identified using specific ionization measurements in the CDC, pulse heights from the aerogel Čerenkov counters (ACC), and timing information from the time-of-flight counters. A detailed description of the Belle detector can be found elsewhere [4].

Hadronic events are separated from QED,  $\tau\tau$ , two-photon, and beam-gas interaction backgrounds by requiring the presence of at least three charged tracks ( $N_{\text{ch}} \geq 3$ ), an event vertex with radial ( $r\phi$ ), and  $z$  coordinates within 1.5 and 3.5 cm of the origin, a total reconstructed center-of-mass (c.m.) energy greater than  $0.2\sqrt{s}$  ( $\sqrt{s}$  is the c.m. collision energy), a  $z$  component of the net reconstructed c.m. momentum less than  $0.5\sqrt{s}/c$ , a total ECL energy between  $0.1\sqrt{s}$  and  $0.8\sqrt{s}$  with at least two energy clusters associated, and  $R_2$ , the ratio of second and zeroth Fox-Wolfram moments [5], less than 0.8.

Candidate  $J/\psi$  mesons are reconstructed using the leptonic decays  $J/\psi \rightarrow \mu^+\mu^-$  and  $e^+e^-$ . For  $J/\psi \rightarrow \mu^+\mu^-$ , both charged tracks must be identified as muons in the KLM using information on hit positions and penetration depth. For  $J/\psi \rightarrow e^+e^-$ , oppositely charged track pairs must be identified as electrons based on a

combination of CDC  $dE/dx$  information, ACC response, and the position, shape, and energy of the associated ECL shower. To correct for final state radiation and bremsstrahlung, photons within 50 mrad of the  $e^\pm$  are included in the  $e^+e^-$  invariant mass calculation. The two lepton candidate tracks are required to have a common vertex, with a distance in the  $r\phi$  plane to the average interaction point (IP)  $d_{r\phi} < 500 \mu\text{m}$ , the IP dimensions being typically  $100 \mu\text{m}$  ( $x$ ) by  $3 \mu\text{m}$  ( $y$ ). The signal region is defined by the mass window, common for both channels,  $-93 < M_{l^+l^-} - M_{J/\psi} < 33 \text{ MeV}/c^2$ , to include  $J/\psi \rightarrow e^+e^-$  events which fall in the radiative tail even after the radiative photon correction. We reconstruct  $\psi(2S) \rightarrow J/\psi \pi^+ \pi^-$  decays by combining  $J/\psi$  candidates with  $\pi^+ \pi^-$  pairs and requiring a common  $\pi^+ \pi^-$  vertex. Candidate  $\chi_{c1}$  and  $\chi_{c2}$  mesons are reconstructed via their radiative decays to the  $J/\psi$ : we combine  $J/\psi$  candidates with photons detected in the ECL that are not associated with an identified  $\pi^0$ , by requiring  $|m_{\gamma\gamma} - m_{\pi^0}| < 16.5 \text{ MeV}/c^2$  ( $3\sigma$ ). The largest source of secondary charmonia in the  $Y(4S)$  sample, due to  $B$  meson decays, is eliminated by requiring the charmonium momentum  $p^*$ , in the initial  $e^+e^-$  center-of-mass system, to be above the  $B$  decay kinematic limit. A common requirement  $p^* > 2.0 \text{ GeV}/c$  is used for all analyses [ $J/\psi$ ,  $\psi(2S)$ ,  $\chi_{c1}$  and  $\chi_{c2}$ ]: this value is robust against the effects of momentum measurement errors and the motion of the  $B$  meson in the c.m. This requirement is not applied to off-resonance data.

The background due to initial state radiation with a hard photon ["radiative return to  $J/\psi(\psi(2S))$ "] [6] and higher order QED processes  $e^+e^- \rightarrow J/\psi\gamma^*$ ,  $J/\psi l^+ l^-$  [7] is also large. This background contributes mainly to  $N_{\text{ch}} = 3$  and  $N_{\text{ch}} = 4$  events, and a dedicated study was performed for each of these samples. The  $J/\psi$  mass peak for  $N_{\text{ch}} = 3$  has a signal-to-background ratio  $S/B \approx 0.1$ , which is too poor to be included in the final signal sample. For  $N_{\text{ch}} = 4$  the  $S/B$  ratio is acceptable, but 85% of the  $J/\psi$  mesons are due to QED processes, principally  $e^+e^- \rightarrow \psi(2S)\gamma \rightarrow J/\psi \pi^+ \pi^- (\gamma)$  with or without a visible photon. Based on this study we require  $N_{\text{ch}} > 4$  to suppress the QED backgrounds, and account for the loss of low multiplicity signal events in the efficiency calculation. The remaining QED background in  $N_{\text{ch}} > 4$  events is suppressed by rejecting events with a  $\psi(2S) \rightarrow J/\psi \pi^+ \pi^-$  candidate accompanied by either a photon with c.m. energy  $E^* > 3.5 \text{ GeV}$  or electron tracks from photon conversion.

Mass distributions for prompt  $J/\psi$  candidates in the  $Y(4S)$  and continuum data samples are shown in Fig. 1. Clear signals are observed both in the off-resonance ( $226 \pm 23$  events) and the  $Y(4S)$  ( $1459 \pm 57$  events) data, for both decay channels. The average detection efficiency for  $J/\psi \rightarrow e^+e^- (\mu^+ \mu^-)$  is, as determined in the Monte Carlo (MC) simulations, 38% (48%).

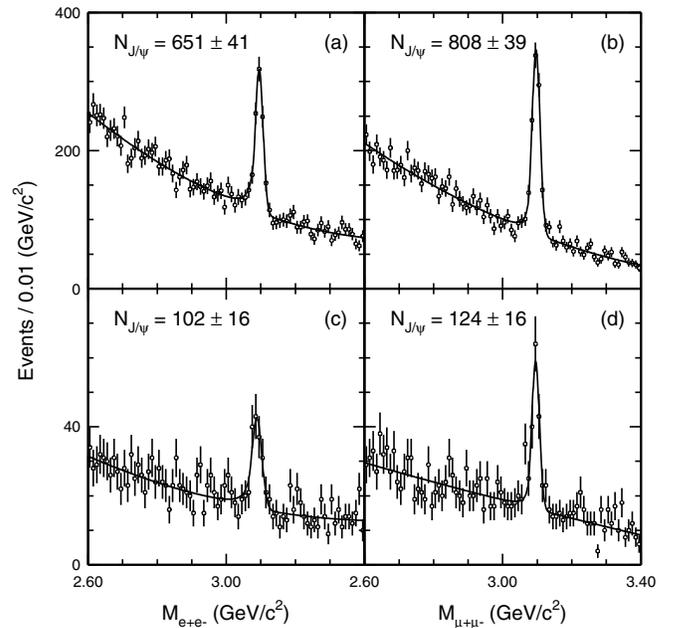


FIG. 1. Mass distributions for the  $J/\psi \rightarrow e^+e^-$  (a),(c) and  $\mu^+ \mu^-$  (b),(d) candidates; (a) and (b) are for  $Y(4S)$  data with  $p^* > 2 \text{ GeV}/c$ ; (c) and (d) are for off-resonance data.  $N_{J/\psi}$  is the number of  $J/\psi$  mesons determined by a fit to the dilepton mass distribution, where a phenomenological line shape function is used for the signal and the background is described by a polynomial.

The  $\psi(2S)$  signal in  $Y(4S)$  data with  $p^* > 2 \text{ GeV}/c$  is shown in Fig. 2(a). Combining  $J/\psi \rightarrow e^+e^-$  and  $\mu^+ \mu^-$ , a clear signal of  $143 \pm 19$  events is seen in the mass difference  $M_{l^+l^- \pi^+ \pi^-} - M_{l^+l^-}$  distribution. In the off-resonance data, no statistically significant  $\psi(2S)$  signal is seen ( $10 \pm 5$  events); this is not inconsistent with the observed rate at the  $Y(4S)$  resonance. Searching for  $\chi_{c1}$  and  $\chi_{c2}$  in the  $Y(4S)$  data, we form the mass difference  $M_{l^+l^- \gamma} - M_{l^+l^-}$ ; no significant signals are seen [Fig. 2(b)]. The average detection efficiency for  $\psi(2S)$  and  $\chi_{c1}$ ,  $\chi_{c2}$  is 20% and 21%, respectively.

We first compare  $J/\psi$  production for  $p^* > 2 \text{ GeV}/c$  in the  $Y(4S)$  and continuum data samples by extracting the number of signal events from invariant mass distributions for 300  $\text{MeV}/c$  wide  $p^*$  bins. The shape and normalization of the resulting  $p^*$  distribution for the off-resonance continuum (not shown) agree very well with those for the  $Y(4S)$  data, indicating that all the  $J/\psi$  production at the  $Y(4S)$  can be explained by continuum production. The branching fraction for the decay  $Y(4S) \rightarrow J/\psi X$  can be estimated from the difference between the normalized yields [ $1459 \pm 57$  and  $1496 \pm 145$  from the  $Y(4S)$  and off-resonance data, respectively] which is found to be  $-37 \pm 156$ . We therefore set an upper limit  $\mathcal{B}(Y(4S) \rightarrow J/\psi X) < 1.9 \times 10^{-4}$  (at 95% C.L.) using the Feldman-Cousins method [8]. This limit is more stringent than the result of Ref. [9]. There are no published predictions for  $\mathcal{B}(Y(4S) \rightarrow J/\psi X)$ .

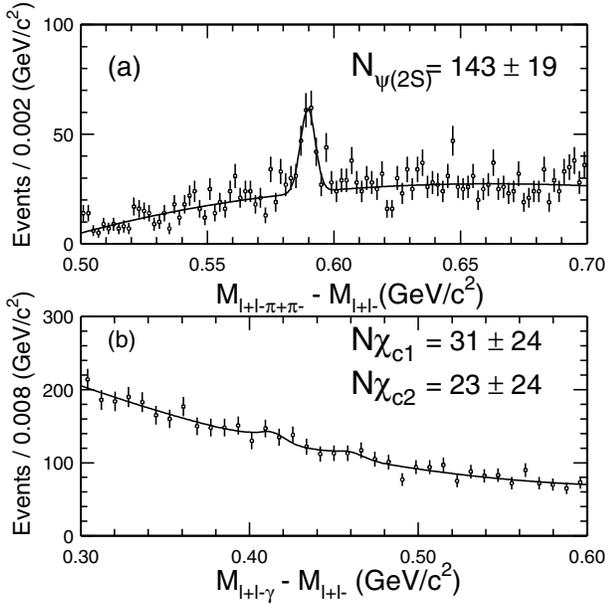


FIG. 2. Mass difference distributions for charmonium candidates in the  $Y(4S)$  data: (a)  $M_{l+l-\pi+\pi^-} - M_{l+l^-}$  for  $\psi(2S)$  candidates with  $p^* > 2$  GeV/c. (b)  $M_{l+l-\gamma} - M_{l+l^-}$  for  $\chi_{c1,c2}$  candidates with  $p^* > 2$  GeV/c. The curves represent fit results with a phenomenological line shape for the signal and a polynomial for the background.

Hereafter we assume that all prompt  $J/\psi$ 's produced at  $\sqrt{s} \approx 10.6$  GeV are due to continuum production. We combine off-resonance data with the  $Y(4S)$  data for  $p^* > 2$  GeV/c to extract charmonium production cross sections and angular distributions. Acceptance corrections are determined using a dedicated Monte Carlo simulation of the process  $e^+e^- \rightarrow J/\psi(\psi(2S))q\bar{q}$ , where the composition of  $q\bar{q}$  flavors is set to that observed at  $\sqrt{s} \approx 10.6$  GeV. To minimize model dependence of the efficiency determination, the data are corrected using a two-dimensional acceptance weight matrix as a function of  $p^*$  and  $\cos\theta^*$ , where  $\theta^*$  is the  $J/\psi$  production angle in the c.m. system. The momentum range  $p^* > 2$  GeV/c is divided into three bins, and  $\cos\theta^*$  is divided into five bins; the number of signal events in each two-dimensional bin is obtained by fitting the invariant mass distribution. A similar procedure is applied to determine the  $\psi(2S)$  acceptance for  $p^* > 2$  GeV/c, while acceptance corrections for  $\chi_{c1,c2}$  were estimated directly from the MC without binning.

The resulting cross sections are summarized in Table I. For the  $J/\psi$  sample ( $p^* > 2$  GeV/c), the feed-down from prompt  $\psi(2S)$  is measured to be  $0.33 \pm 0.04^{+0.05}_{-0.06}$  pb, and this contribution is subtracted to give the direct  $J/\psi$  cross section in the table. The  $p^* < 2$  GeV/c off-resonance data are used to extend the  $J/\psi$  cross-section measurement to the full  $p^*$  range. As we observe no significant signal in the continuum for  $\psi(2S)$ ,  $\chi_{c1}$ , and  $\chi_{c2}$ , we estimate cross sections for  $p^* > 2$  GeV/c only.

For the systematic errors of the measured cross sections the following contributions are considered (where appropriate): uncertainty in the efficiency determination ( $\pm 5\%$ ), effects of the multiplicity cut ( $+4\%$ ), lepton identification ( $\pm 4\%$ ), tracking ( $\pm 4\%$ ), luminosity measurement ( $\pm 1.3\%$ ), possible feed-down from the  $\chi_{c1,c2}$  ( $-10\%$ ), contamination from QED processes ( $-4\%$ ),  $\psi(2S)$  feed-down subtraction ( $\pm 2\%$ ), and errors of the respective branching fractions. A contribution from the unobserved process  $Y(4S) \rightarrow J/\psi X$  is not included. If the true branching fraction for this decay were just below the determined upper limit, the measured  $J/\psi$  cross sections would be overestimated by  $\sim 0.18$  pb. Other sources of systematic error, such as contamination from radiative return to the  $Y(1S, 2S, 3S)$  and from  $\gamma\gamma \rightarrow \chi_{c2}$ , were found to be negligible. As an additional check,  $J/\psi$  cross sections were determined separately for the  $e^+e^-$  and  $\mu^+\mu^-$  decays, and found to be in good agreement: their ratio is  $1.00 \pm 0.07 \pm 0.04$ .

Our results on the  $J/\psi$  total and partial cross section,  $1.47 \pm 0.10 \pm 0.13$  pb and  $1.05 \pm 0.04 \pm 0.09$  pb, respectively, are smaller than those of BABAR [9]. The partial cross sections for direct  $J/\psi$  and prompt  $\psi(2S)$  production represent the first measurements in  $e^+e^-$  collisions.

NRQCD predictions for  $\sigma(e^+e^- \rightarrow J/\psi_{\text{direct}} X)$  cover the range 0.8–1.7 pb [10–12]. (We exclude the extreme value of Ref. [7].) The most recent analysis [12] obtains a total cross section of 0.8–1.1 pb, attributing 0.3 pb and 0.5–0.8 pb to color-singlet and color-octet mechanisms, respectively. Our result can be used to further constrain the combination of color-octet matrix elements needed in the calculation [10,12].

Momentum distributions are shown in Fig. 3. The distribution of feed-down from  $\psi(2S)$  to  $J/\psi$  is also shown in Fig. 3(a). The  $J/\psi$  distribution vanishes  $\sim 300$  MeV/c below the kinematical limit (4.84 GeV/c) while the

TABLE I. The measured charmonium cross sections. The upper limits for  $\chi_{c1}$  and  $\chi_{c2}$  are at the 90 C.L.

$\sigma$ [pb]	$0 < p^* < p^*_{\text{max}}$ [GeV/c]	$2.0 < p^* < p^*_{\text{max}}$ [GeV/c]
$\sigma(e^+e^- \rightarrow J/\psi X)$	$1.47 \pm 0.10 \pm 0.13$	$1.05 \pm 0.04 \pm 0.09$
$\sigma(e^+e^- \rightarrow J/\psi_{\text{direct}} X)$	...	$0.72 \pm 0.08^{+0.13}_{-0.17}$
$\sigma(e^+e^- \rightarrow \psi(2S) X)$	...	$0.67 \pm 0.09^{+0.09}_{-0.11}$
$\sigma(e^+e^- \rightarrow \chi_{c1} X)$	...	$< 0.35$
$\sigma(e^+e^- \rightarrow \chi_{c2} X)$	...	$< 0.66$

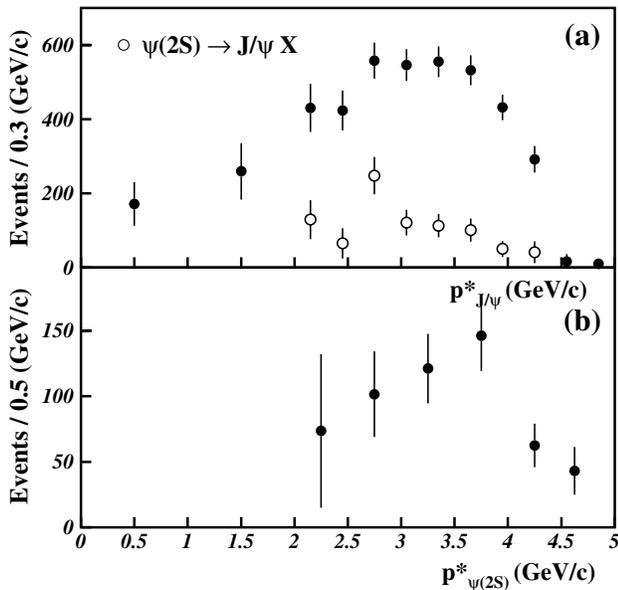


FIG. 3. c.m. momentum distributions of prompt charmonia, corrected for efficiency: (a)  $J/\psi$  (filled points) and  $J/\psi$  mesons from  $\psi(2S) \rightarrow J/\psi X$  (open points); (b)  $\psi(2S)$ .

$\psi(2S)$  momentum distribution extends till the end point (4.65 GeV/c). The  $J/\psi$  momentum distribution agrees qualitatively with the predicted shape of the color-singlet  $J/\psi c\bar{c}$  component [11,13]. The predicted color-singlet  $J/\psi gg$  and color-octet  $J/\psi g$  momentum distributions [11,13] extend to the highest momenta, where we do not observe the signal. Some NRQCD calculations also predict a dramatic rise in the cross section at the end point due to color octet  $e^+e^- \rightarrow J/\psi g$  [13,14]. The detection efficiency for this process was studied using a dedicated generator embedded in PYTHIA [15]. Assuming a 1 pb cross section for this process, we expect  $>300$  events in the last two bins of Fig. 3(a). No such signal is observed.

The distributions of the prompt  $J/\psi$  c.m. production angle  $\theta^*$ , and the helicity angle  $\theta_H$  (the angle between the positive lepton daughter momentum vector in the  $J/\psi$  rest frame and the  $J/\psi$  momentum vector in the c.m. system) have also been studied in different momentum intervals. We correct the distributions for detection efficiency, but ignore possible effects due to feed-down. The distributions are fitted with the parametrizations  $1 + A \cos^2 \theta^*$  and  $1 + \alpha \cos^2 \theta_H$ ; the results are summarized in Table II, with selected fits also shown in Fig. 4. No statistically significant  $p^*$  dependence is seen for either  $A$  or  $\alpha$  parameters.

A large positive  $A$  at all momenta for direct  $J/\psi$  production is expected only for the color-singlet  $J/\psi c\bar{c}$  mechanism [13]. However, its contribution to the cross section is thought to be small ( $\sim 10\%$ ) [11,13]. The leading color octet process  $J/\psi g$  is expected to yield  $A \approx +1$  at the end point [13,14], although as noted above we do not observe these events in the  $p^*$  distribution. A significant longitudinal polarization of direct  $J/\psi$  mesons

TABLE II. Results of the fits to angular distributions.

$p_{J/\psi}^*$ [GeV/c]	$A$	$\chi^2/\text{d.o.f.}$	$\alpha$	$\chi^2/\text{d.o.f.}$
2.0–2.6	$0.3^{+0.5}_{-0.4}$	1.5/4	$-0.4 \pm 0.2$	7.8/4
2.6–3.4	$1.1^{+0.4}_{-0.3}$	5.0/4	$-0.4 \pm 0.1$	1.3/4
3.4–4.9	$1.1^{+0.4}_{-0.3}$	4.5/4	$-0.2 \pm 0.2$	7.1/4
2.0–3.4	$0.7 \pm 0.3$	1.2/4	$-0.5 \pm 0.1$	4.6/4
2.0–4.9	$0.9 \pm 0.2$	3.0/4	$-0.4 \pm 0.1$	13.4/4

( $\alpha < -0.4$ ) is expected for the color-singlet process  $J/\psi gg$  alone [11].

In summary, we have observed production of prompt  $J/\psi$  and  $\psi(2S)$  at energies near the  $Y(4S)$  mass. We set an upper limit for  $J/\psi$  production from  $Y(4S)$  (valid for  $p^* > 2$  GeV/c),  $\mathcal{B}(Y(4S) \rightarrow J/\psi X) < 1.9 \times 10^{-4}$  at the 95% C.L., and find the total cross section for continuum prompt  $J/\psi$  production to be  $\sigma(e^+e^- \rightarrow J/\psi X) = 1.47 \pm 0.10(\text{stat}) \pm 0.13(\text{syst})$  pb. In the momentum range  $p^* > 2$  GeV/c, we measure  $\sigma(e^+e^- \rightarrow J/\psi_{\text{direct}} X) = 0.72 \pm 0.08^{+0.13}_{-0.17}$  pb and  $\sigma(e^+e^- \rightarrow \psi(2S) X) = 0.67 \pm 0.09^{+0.09}_{-0.11}$  pb. The angular distribution of prompt  $J/\psi$  mesons follows  $1 + A \cos^2 \theta^*$  with  $A = 0.9 \pm 0.2$ , and the helicity angle follows  $1 + \alpha \cos^2 \theta_H$  with  $\alpha = -0.4 \pm 0.1$ , indicating partial longitudinal polarization. We do not observe a statistically significant variation of  $A$  or  $\alpha$  with momentum.

We thank the KEKB accelerator group for the excellent operation of the accelerator. We acknowledge support from the Ministry of Education, Culture, Sports, Science, and Technology of Japan and the Japan Society for the

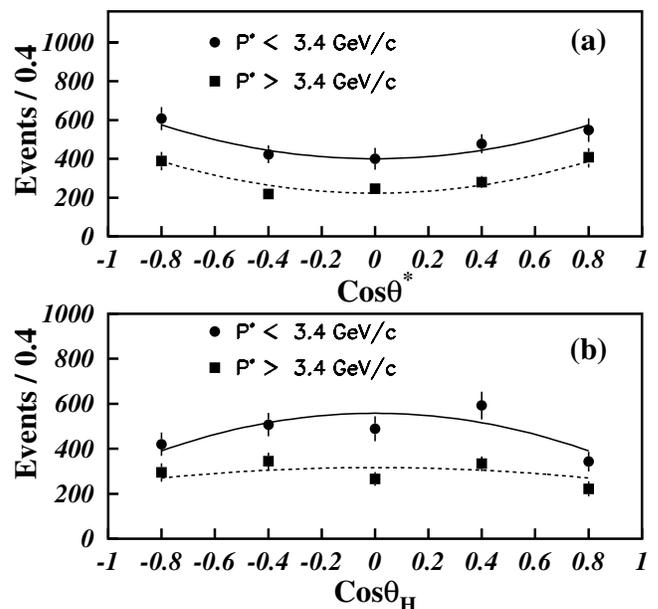


FIG. 4. The  $\cos \theta^*$  (a) and  $\cos \theta_H$  (b) distributions for low and high  $p^*$ . The curves represent fit results, described in the text and summarized in Table II.

Promotion of Science; the Australian Research Council and the Australian Department of Industry, Science and Resources; the Department of Science and Technology of India; the BK21 program of the Ministry of Education of Korea and the CHEP SRC program of the Korea Science and Engineering Foundation; the Polish State Committee for Scientific Research under Contract No. 2P03B 17017; the Ministry of Science and Technology of the Russian Federation; the National Science Council and the Ministry of Education of Taiwan; and the U.S. Department of Energy.

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\*On leave from University of Toronto, Toronto, Ontario, Canada.

- [1] G. T. Bodwin, E. Braaten, and G. P. Lepage, Phys. Rev. D **51**, 1125 (1995).
- [2] For a recent review, see M. Kramer, Prog. Part. Nucl. Phys. **47**, 141 (2001).
- [3] KEKB B Factory Design Report No. 95-7 1995 (unpublished).
- [4] Belle Collaboration, K. Abe *et al.*, KEK Report No. 2000-4 (to be published).
- [5] G. C. Fox and S. Wolfram, Phys. Rev. Lett. **41**, 1581 (1978).
- [6] M. Benayoun, S. I. Eidelman, V. N. Ivanchenko, and Z. K. Silagadze, Mod. Phys. Lett. A **14**, 2605 (1999).
- [7] C.-H. Chang, C.-F. Qiao, and J.-X. Wang, Phys. Rev. D **57**, 4035 (1998).
- [8] G. J. Feldman and R. D. Cousins, Phys. Rev. D **57**, 3873 (1998).
- [9] BABAR Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **87**, 162002 (2001).
- [10] F. Yuan, C.-F. Qiao, and K.-T. Chao, Phys. Rev. D **56**, 321 (1997); **56**, 1663 (1997).
- [11] S. Baek, P. Ko, J. Lee, and H. S. Song, J. Korean Phys. Soc. **33**, 97 (1998); hep-ph/9804455.
- [12] G. A. Schuler, Eur. Phys. J. C **8**, 273 (1999).
- [13] P. Cho and A. K. Leibovich, Phys. Rev. D **54**, 6690 (1996).
- [14] E. Braaten and Yu-Qi Chen, Phys. Rev. Lett. **76**, 730 (1996).
- [15] T. Sjöstrand, PYTHIA 5.7/JETSET 7.4; Report No. CERN-TH.7112/93, 1993; T. Sjöstrand, Comput. Phys. Commun. **82**, 74 (1994).