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Inclusive decays of B-meson to J/ψ and χ_{c1} using $386 \times 10^6 B\bar{B}$ events

RAJEEV KUMAR
Department of Math. Stat. & Physics, Punjab Agricultural University, Ludhiana 141 004, India
E-mail: rajeevsharma@pau.edu

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Abstract. The inclusive decays of B-mesons to charmonium have been studied in a data sample of 386 million $B\bar{B}$ events. The data sample has been collected by the Belle detector at the KEKB asymmetric energy e^+e^- collider operating at the $\Upsilon(4S)$ resonance. The branching fractions have been measured for the inclusive decays to $J/\psi + X$ and $\chi_{c1} + X$. The measured branching fraction for $J/\psi + X$ is $\mathcal{B}(B \to J/\psi(\to e^+e^-) + X) = (1.10 \pm 0.005 \pm 0.057)\%$ and $\mathcal{B}(B \to J/\psi(\to \mu^+\mu^-) + X) = (1.08 \pm 0.004 \pm 0.056)\%$, while the inclusive $\chi_{c1} + X$ branching fraction is found to be $\mathcal{B}(B \to \chi_{c1} + X) = (0.44 \pm 0.01 \pm 0.06)\%$. The feed-down contribution from higher charmonium states is subtracted from the measured branching fractions and the direct branching fractions are obtained to be $\mathcal{B}(B \to J/\psi + X) = (0.77 \pm 0.04 \pm 0.06)\%$ and $\mathcal{B}(B \to \chi_{c1} + X) = (0.41 \pm 0.01 \pm 0.06)\%$.

Keywords. B-meson; CP violation; charmonium; B-factory; Belle detector.

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1. Inroduction

Charmonium ($c\bar{c}$) is a bound state of charm and anticharm quarks. Being a composite particle, charmonium can exist in a number of different energy states. Charmonium physics has played an important role in the study of quantum chromodynamics (QCD), both perturbatively and non-perturbatively, since the first charmonium state J/ψ was discovered in 1974 [1,2]. These spin-1S-wave resonances are of special experimental significance because they have extremely clean signatures through their leptonic decay modes. The production rate of charmonium states in various high-energy physics processes offers an insight not only into the interaction between a heavy quark and antiquark but also into the elementary processes which produce the $q\bar{q}$ pair. One of the production processes for the charmonium states is the decay of a B-meson. The basic decay mechanism for B-mesons is the spectator diagram shown in figure 1a. The dominant mechanism for the production of charmonium, however, is the colour-suppressed internal spectator diagram, shown

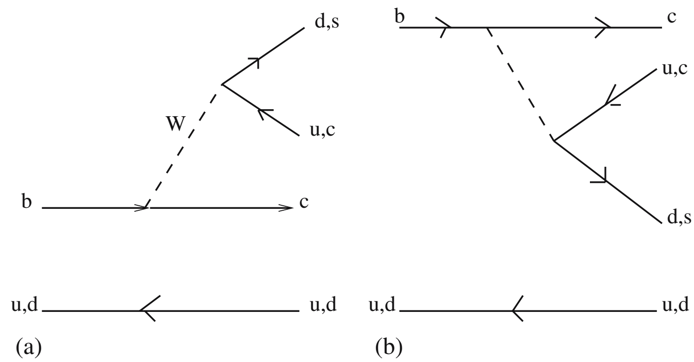

Figure 1. The spectator diagrams for B-meson decays.

in figure 1b. Inclusive decays of B-mesons to charmonium states provide a testing ground for QCD calculations of quark dynamics. The factorization formulation [3] of non-relativistic QCD (NRQCD) provides a rigorous theoretical framework for the description of heavy quarkonium production and decay, predicting the existence of colour-octet processes in nature [4,5]. In this approach, production rates are expressed as the multiplication of perturbatively calculable patronic cross-section and non-perturbative constants called NRQCD matrix elements [6]. The reconstruction and study of charmonium states viz., J/ψ, $\psi(2S)$ and χ_{c1} in B decays is a crucial component of the measurement of time-dependent CP-violating asymmetries [7,8] and other tests of the Standard Model [9].

In this paper, inclusive branching fraction measurements of B decay to the J/ψ and χ_{c1} states have been performed using the $J/\psi \to \ell^+\ell^-$ and $\chi_{c1} \to J/\psi(\to \ell^+\ell^-)\gamma$ decays, where the lepton ℓ may be either an electron or a muon.

2. The KEKB accelerator and Belle detector

The KEKB accelerator [10] is an asymmetric-energy e^+e^- collider designed to produce a large number of $B\bar{B}$ pairs at a center-of-mass energy of $\sqrt{s} = 10.58$ GeV, corresponding to the mass of the $\Upsilon(4S)$ resonance. This resonance is a bound state of $b\bar{b}$ quarks and its rest energy of 10.58 GeV is just above the threshold of B-meson pair production. It decays exclusively into quantum mechanically entangled $B\bar{B}$ pairs. The positrons use a low-energy ring (LER) with energy $E^+ = 3.5$ GeV and a current of about 1600 mA. The electrons use a high-energy ring (HER) with energy $E^- = 8.0$ GeV with a current of 1200 mA. As a result of the energy asymmetry, the $\Upsilon(4S)$ resonance is not at rest in the lab frame. It is boosted and this boost causes a spatial separation of the produced B-mesons and provides a chance to measure the difference in the decay times of the B-mesons.

The Belle detector is a large solid-angle magnetic spectrometer which is situated at the interaction point (IP) of KEKB accelerator. Closest to the IP is a silicon vertex detector (SVD), surrounded by a 50-layer central drift chamber (CDC), an array of aerogel Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight (TOF) scintillation counters, and an electromagnetic calorimeter (ECL) comprising CsI(Tl) crystals. These subdetectors are located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return yoke located outside the coil is instrumented to detect K_L^0 mesons and muons (KLM). The detector is described in detail elsewhere [11].

3. Dataset and event selection

The dataset used in this analysis consists of 386 million $B\bar{B}$ pairs collected with the Belle detector at the KEKB asymmetric-energy e^+e^- collider: the first 152×10^6 B-meson pairs were collected with a beam pipe of 2.0 cm radius and a three-layer SVD, and the remaining 234×10^6 B-meson pairs with a beam pipe of 1.5 cm radius, a four-layer SVD and a small-cell inner drift chamber [12,13].

Events with B-meson candidates are first selected by applying general hadronic event selection criteria. These include a requirement on charged tracks (at least three of them should originate from an event vertex consistent with the interaction region), a requirement on the reconstructed centre-of-mass (CM) energy ($E^{\mathrm{CM}} > 0.2\sqrt{s}$, where $\sqrt{s}$ is the total CM energy), a requirement on the longitudinal (z-direction) component of the reconstructed CM momentum with respect to the beam direction ($|p_z^{\mathrm{CM}}| < 0.5\sqrt{s}/c$) and a requirement on the total ECL energy ($0.1\sqrt{s} < E_{\mathrm{ECL}}^{\mathrm{CM}} < 0.8\sqrt{s}$) with at least two energy clusters. To suppress continuum background, we also require that the ratio of the second and zeroth Fox–Wolfram moments [14] be less than 0.5. To remove charged particle tracks that are poorly measured or do not come from the interaction region, we require their origin within 0.5 cm in radial direction and 5 cm along the beam direction with respect to the interaction point.

4. Selection of J/ψ and χ_{c1}

The J/ψ resonance is reconstructed via the decay mode $J/\psi \to \ell^+\ell^-$, where ℓ is the muon or the electron. For muon tracks, identification is based on track penetration depth and the hit pattern in the KLM system. A track is identified as muon track if its muon likelihood ratio $\mathcal{R}(\mu)$ is greater than 0.1, where $\mathcal{R}(\mu) = \mathcal{L}_\mu/(\mathcal{L}_\mu + \mathcal{L}_\pi + \mathcal{L}_K)$, with $\mathcal{L}_\mu$, $\mathcal{L}_\pi$ and $\mathcal{L}_K$ the likelihoods for a track to be muon, pion and kaon. Electron tracks are identified by a combination of $\mathrm{d}E/\mathrm{d}x$ from the CDC, E/p (E is the energy deposited in the ECL and p is the momentum measured by the SVD and the CDC) and shower shape in the ECL. In order to recover dielectron events in which one or both electrons are radiating a photon, the four-momenta of all photons within 0.05 radian of the e^+ or e^- directions are included in the invariant mass calculation. The invariant mass windows are $-0.06(-0.15)\ \mathrm{GeV/c^2} \leq M_{\ell^+\ell^-} - M_{J/\psi} \leq 0.036\ \mathrm{GeV/c^2}$ to select J/ψ candidates in the $\mu^+\mu^-(e^+e^-)$ channels, where $M_{J/\psi}$ denotes the world average of J/ψ mass [15]; these intervals are asymmetric in order to include part of the radiative tails. Vertex fit is performed for selected J/ψ candidates to improve the momentum resolution.

The χ_{c1} state is reconstructed via the decay mode $\chi_{c1} \to \gamma J/\psi$ with $J/\psi \to \ell^+\ell^-$, where ℓ is the muon or the electron. Photons are identified as ECL energy clusters that do not have a spatial match with a charged track, and that have a minimum energy of 0.060 GeV. We also reject the primary photon candidate if the ratio of the energy in the array of the central 3×3 ECL cells to that of 5×5 cells is less than 0.87. Finally, the χ_{c1} state is reconstructed by combining a J/ψ candidate with momentum below

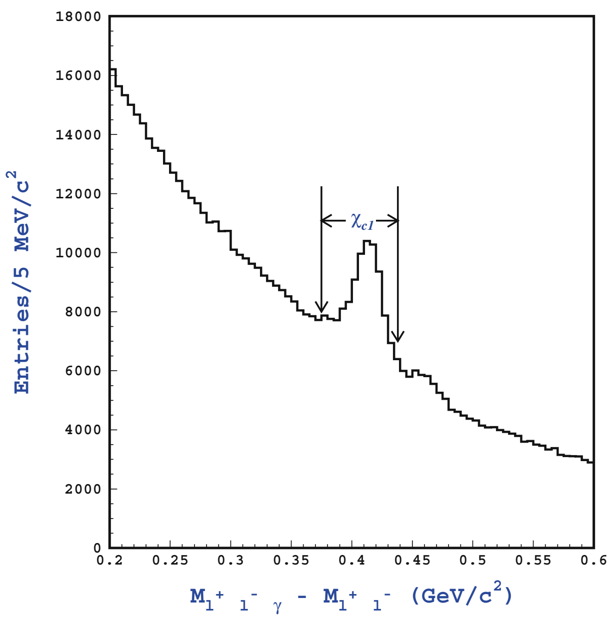

Figure 2. The mass difference $\Delta M(M_{\ell^+\ell^-\gamma} - M_{\ell^+\ell^-})$ distribution for the inclusive χ_{c1} candidates. The enhancement just above the χ_{c1} mass region is due to χ_{c2}.

2.0 GeV/c in the CM frame with a selected photon; to suppress $\pi^0 \rightarrow \gamma\gamma$, we veto photons that, when combined with another photon in an event, satisfy 0.110 GeV/c^2 $\leq m_{\gamma\gamma} \leq$ 0.150 GeV/c^2. The χ_{c1} candidates are selected by requiring the mass difference ($\Delta M = M_{\ell^+\ell^-\gamma} - M_{\ell^+\ell^-}$) to lie between 0.370 GeV/c^2 and 0.438 GeV/c^2. The parameter ΔM is used to extract the signal yield so that the distribution is primarily dominated by the gamma energy resolution. The ΔM distribution is shown in figure 2.

5. Results

The signal reconstruction efficiency is the fraction of reconstructed signal events which pass all the event selection criteria. The efficiency is estimated from pure Monte Carlo (MC) samples, where events are generated by using EvtGen [16]. The response of the Belle detector is simulated using GEANT4-based program which accommodates the geometry of each detector component [17]. The reconstruction efficiency for $J/\psi \rightarrow \ell^+\ell^-$ (where $\ell = \mu$ or e) is determined by performing a fit to the J/ψ mass distribution and that for $\chi_{c1} \rightarrow J/\psi\gamma$ is determined by performing a fit to the $\Delta M(\chi_{c1} - J/\psi)$ mass distribution. We obtained reconstruction efficiencies $(40.5 \pm 0.5)\%$ and $(44.9 \pm 0.6)\%$ for the $J/\psi \rightarrow e^+e^-$ and the $J/\psi \rightarrow \mu^+\mu^-$ decay modes, respectively, and $(37.3 \pm 0.3)\%$ for the $\chi_{c1} \rightarrow J/\psi\gamma$ mode, where the error is due to the statistics of the MC sample.

The signal yield is extracted by performing a binned maximum likelihood fit to the J/ψ mass distribution of the selected candidates. For inclusive $B \rightarrow J/\psi + X$ mode, we fit the distribution with a crystal ball function for the signal and a third-order Chebyshev polynomial for the combinational background as shown in figure 3. A yield of 102559.0 ± 456.9 events is obtained for the $J/\psi \to e^+e^-$ mode and 111442.47 ± 392.7 events for the $J/\psi \to \mu^+\mu^-$ mode.

For inclusive $B \to \chi_{c1} + X$ mode, a binned maximum likelihood fit is performed to the ΔM mass distribution, as shown in figure 2. A clear χ_{c2} peak can also be seen next to a larger peak due to χ_{c1}. The signal yield is extracted by fitting the distribution to two crystal ball line function and a third-order Chebyshev polynomial for the combinatorial background. The signal line shape parameters of the second crystal ball function viz., width, mean and tail parameters are allowed to float in this fit with the following constraints: the difference between the means is fixed to the known $\chi_{c1} - \chi_{c2}$ mass difference; the MC expected ratio of widths is taken into account by fixing the width to 1.1 times the width of χ_{c1}, which is consistent with higher average photon energy; and the tail parameters are fixed to that obtained from MC study. The obtained signal yield is 25506.84 ± 338.34 events (figure 4).

The branching fraction ($\mathcal{B}$) for the $B \to J/\psi(\chi_{c1}) + X$ decay mode is calculated as follows:

$$\mathcal{B} = \frac{N_{\text{sig}}}{\epsilon \times N_{B\bar{B}} \times \mathcal{B}_{\text{sec}}}, \tag{1}$$

where N_{sig} is the observed signal yield, $\epsilon(N_{B\bar{B}})$ is the reconstruction efficiency (number of B-mesons in the data sample) and $\mathcal{B}_{\text{sec}}$ is the secondary branching ratio. We use the daughter branching fractions published in ref. [15]. Production of neutral and charged B-meson pairs in $\Upsilon(4S)$ decay is assumed to be equal.

The systematical uncertainties are summarized in table 1. Significant sources of systematic uncertainty are in the tracking efficiency (1.0% per track), lepton identification (2.0% per lepton track), photon detection efficiency (2.0%) and daughter branching fractions (0.7% for $J/\psi \to \ell^+\ell^-$, 12.2% for $\chi_{c1} \to J/\psi(\to \ell^+\ell^-)\gamma$). The total systematic error is the sum of all these uncertainties in quadrature.

The resulting branching fraction is $(1.10 \pm 0.005 \pm 0.057)\%$ for $B \to J/\psi(\to e^+e^-) + X$ and $(1.08 \pm 0.004 \pm 0.056)\%$ for $B \to J/\psi(\to \mu^+\mu^-) + X$, where the first error is

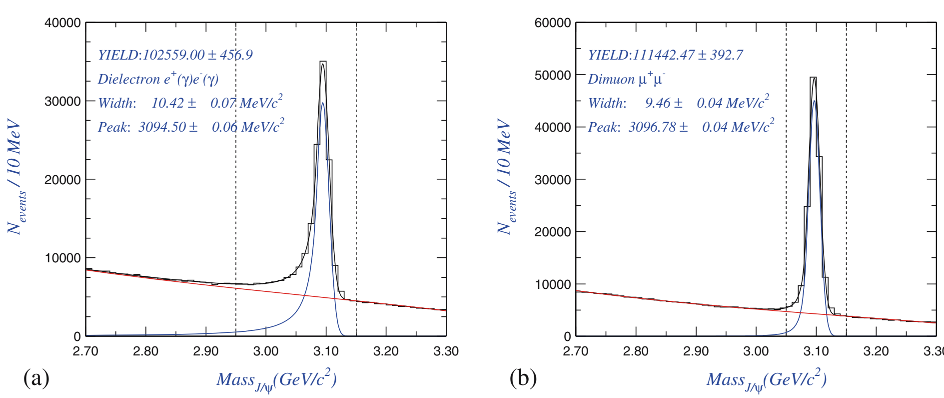

Figure 3. The fitted invariant J/ψ mass distribution for (**a**) $J/\psi \to e^+e^-$ and (**b**) $J/\psi \to \mu^+\mu^-$. The blue and red curves show the signal and the polynomial background component of the fit, respectively.

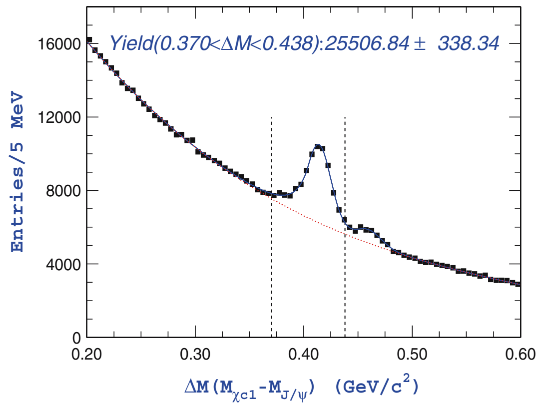

Figure 4. The mass difference $\Delta M(M_{\ell^+\ell^-\gamma} - M_{\ell^+\ell^-})$ distribution for the inclusive χ_{c1} candidates. The enhancement just above the χ_{c1} mass region is due to χ_{c2}.

statistical and second is systematic. The combined branching fraction for inclusive $B \to J/\psi + X$ decay mode is $\mathcal{B}(B \to J/\psi + X) = (1.09 \pm 0.003 \pm 0.057)\%$. However, some of the $B \to J/\psi + X$ decay results from the 'feed-down' from higher mass states such as $\chi_{c1}(\to J/\psi\gamma)$, $\chi_{c2}(\to J/\psi\gamma)$ and $\psi(2S)(\to J/\psi\gamma)$; which are not forbidden by the factorization. The direct decay rate to $J/\psi + X$ state is determined by subtracting the feed-down, which is estimated by using PDG values of branching fractions for $\chi_{c1} \to J/\psi\gamma$, $\chi_{c2}(\to J/\psi\gamma)$ and $\psi(2S)(\to J/\psi\gamma)$. The resultant direct branching fraction for the inclusive $B \to J/\psi + X$ mode is $\mathcal{B}(B \to J/\psi + X) = (0.77 \pm 0.04 \pm 0.06)\%$.

The measured value of the inclusive $B \to \chi_{c1} + X$ branching fraction is $\mathcal{B}(B \to \chi_{c1} + X) = (0.44 \pm 0.01 \pm 0.06)\%$, where the first error is statistical and second is systematic. The measured branching fraction also includes 'feed-down' contribution from higher mass state $\psi(2S)(\to \chi_{c1}\gamma)$. The direct branching fraction comes out to be $\mathcal{B}(B \to \chi_{c1} + X) = (0.41 \pm 0.01 \pm 0.06)\%$, where feed-down contribution, which is estimated based upon PDG value of branching fraction for the $\psi(2S) \to \chi_{c1} + X$ decay, is also subtracted from the measured value of the branching fraction.

Table 1. Summary of systematic errors on branching fraction.

Source	Uncertainty (%) $B \to J/\psi + X$	Uncertainty (%) $B \to \chi_{c1} + X$
Tracking error	2.0	2.0
Lepton identification	4.0	4.0
γ detection	2.0	2.0
MC statistics	1.0	1.0
$N_{B\bar{B}}$	1.2	1.2
Daughter branching fractions	0.7	12.2
Total	5.2	13.2

6. Summary

In summary, the inclusive measurement of branching fraction for $B \to J/\psi + X$ and $B \to \chi_{c1} + X$ decays is reported in this paper. The measured branching fraction for $J/\psi + X$ is $\mathcal{B}(B \to J/\psi(\to e^+e^-) + X) = (1.10 \pm 0.005 \pm 0.057)\%$ and $\mathcal{B}(B \to J/\psi(\to \mu^+\mu^-) + X) = (1.08 \pm 0.004 \pm 0.056)\%$, while the inclusive $B \to \chi_{c1} + X$ branching fraction is $\mathcal{B}(B \to \chi_{c1} + X) = (0.44 \pm 0.01 \pm 0.06)\%$. The measured values are consistent with the previously measured values by CLEO and BaBar Collaborations [18–20]; while statistical uncertainty on the present measurement is improved from that of the previous measurements.

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