STUDY OF CHARMONIUM PRODUCTION AND ELECTROWEAK PENGUINS WITH BABAR

Vuko Brigljević
Lawrence Livermore National Laboratory, 7000 East Ave,
Livermore CA 94550, USA
representing the BABAR Collaboration

We report measurements of charmonium resonances ($J/\psi$, $\psi(2S)$, $\chi_{c1}$) using about 25 $fb^{-1}$ of data collected by the BABAR detector around the $\Upsilon(4S)$ resonance. We present measurements of inclusive charmonium production of charmonium in $B$ decays and from the continuum, as well as exclusive branching ratios of $B$ mesons into charmonium final states. We present also a measurement of the $B^0 \rightarrow K^0\gamma\gamma$ branching ratio and a search for the decay $B^0 \rightarrow \gamma\gamma$.

1 Introduction

We present measurements of charmonium production and processes involving electroweak penguins in $e^+e^-$ collisions at the $\Upsilon(4S)$ resonance, using data taken by the BABAR detector at the PEP-II $B$ factory in 1999 and 2000, which consist of 20.7 $fb^{-1}$ accumulated at the $\Upsilon(4S)$ resonance, and 2.6 $fb^{-1}$ taken off-resonance at an energy 0.04 GeV below the peak. This sample corresponds to $22.7 \cdot 10^6 \Upsilon(4S) \rightarrow BB$ decays.

2 Charmonium production

We reconstruct decays of the charmonium resonances $J/\psi$, $\psi(2S)$ and $\chi_{c1}$. We reconstruct $J/\psi$ and $\psi(2S)$ through their decay into two electrons or two muons; $\psi(2S)$ is also reconstructed through the decay $J/\psi\pi^+\pi^-$. While $\chi_{c1}$ is reconstructed through the decay into $J/\psi\gamma$. As examples, the signals for the decays $J/\psi \rightarrow e^+e^-$, $\chi_{c1} \rightarrow J/\psi\gamma$ ($J/\psi \rightarrow \mu^+\mu^-$) and $\psi(2S) \rightarrow J/\psi\pi^+\pi^- (J/\psi \rightarrow e^+e^-)$ are shown in Fig. 1.

2.1 Inclusive Charmonium studies

Charmonium mesons may be produced: a) as a product of a $B$ meson decay; b) as a direct product of the decay of $\Upsilon(4S)$; c) in the fragmentation process of a continuum $e^+e^- \rightarrow q\bar{q}$ event (prompt production); d) through Initial State Radiation (ISR).

We isolate charmonium mesons from $B$ decays by looking at $B\bar{B}$-like events and by requiring the charmonium momentum in the center of mass frame, $p^*$, to be below the kinematic limit for $B$ decays, less than 2 GeV/c for $J/\psi$ and less than 1.6 GeV/c for $\psi(2S)$. Results for inclusive branching ratios of $B$ mesons into charmonium mesons are listed in Table 1.

We measure the $J/\psi$ polarization by fitting the helicity distribution. The helicity angle, $\Theta_H$, is the angle, measured in the $J/\psi$ rest frame, between the positively charged lepton and the
| Meson     | $\mu\mu/ee$      | $B(\bar{B} \rightarrow \text{Meson X})$ [%] |
|-----------|------------------|------------------------------------------|
| $J/\psi$  | 0.995 ± 0.036    | 1.044 ± 0.013 ± 0.028                      |
| $J/\psi$ direct | 0.999 ± 0.045   | 0.789 ± 0.010 ± 0.034                      |
| $\psi(2S)$ | 0.93 ± 0.15     | 0.275 ± 0.020 ± 0.029                      |
| $\chi_{c1}$ | 1.09 ± 0.21     | 0.378 ± 0.034 ± 0.026                      |
| $\chi_{c1}$ direct | 1.11 ± 0.23    | 0.353 ± 0.034 ± 0.024                      |
| $\chi_{c2}$ | 0.78 ± 0.68     | 0.137 ± 0.058 ± 0.012                      |
| $\chi_{c2}$ limit |             | < 0.21 at 90% C.L.                         |

Table 1: Inclusive Branching Ratios of $B$ mesons into charmonium mesons.

![Figure 1: Charmonium signals, from left to right: $M(e^+e^-)$ for $J/\psi$ $\to e^+e^-$ candidates, $M(\mu\mu\gamma) - M(\mu\mu)$ for $\chi_{c1} \to J/\psi(\mu\mu)\gamma$ candidates and $M(e^+e^-\pi^+\pi^-) - M(e^+e^-)$ for $\psi(2S) \to J/\psi(e^+e^-)\pi^+\pi^-$ candidates.](image)

$J/\psi$ flight direction in the $B$ meson rest frame. The distribution of $u = \cos \Theta_H$ can be written in terms of a polarization parameter $\alpha$: $h(u) = 3(1 + \alpha u^2)/[2(\alpha + 3)]$, where $\alpha = 0$ indicates the distribution is unpolarized, $\alpha = 1$ is transversely polarized and $\alpha = -1$ is longitudinally polarized. We find $\alpha = -0.424 \pm 0.023$ for $J/\psi$ mesons from $B$ decays.

The $J/\psi$ production in the continuum is of particular interest due to the possible contribution of $c\bar{c}$ pairs created in a color octet state, which would enhance prompt $J/\psi$ production. To eliminate background from $B \to J/\psi X$ in the on-peak data sample, we require the $J/\psi$ momentum in the $\Upsilon(4S)$ rest frame to be greater than 2 GeV/c. To suppress ISR production of $J/\psi$ and $\psi(2S)$ and two photon production of $\chi_{c2}$, we require at least 3 quality tracks with $0.41 < \theta < 2.54$, the visible energy of the event be greater than 5 GeV and the ratio of the second to the zeroth Fox-Wolfram moment, $R_2$, to be smaller than 0.5. We then study the production and decay properties of these prompt $J/\psi$ mesons. The distribution of the signal in $\cos \Theta^*$ has been extracted and fit with $1 + A \cos^2 \Theta^*$. Color octet and color singlet models have very different predictions for the value of $A$: at high $p^*$ values, color octet models predict $0.6 < A < 1.0$ while the color singlet model predicts $A \approx -0.8$. We measure $A = 1.5 \pm 0.6$ for $p^* > 3.5$ GeV/c, clearly favoring the presence of color octet contributions. We also measure the polarization for prompt $J/\psi$ to be $\alpha = -0.73 \pm 0.09$.

2.2 Exclusive Charmonium decays

We look for candidate $B$ mesons by combining the reconstructed charmonium mesons with light meson candidates. Two kinematic variables are used to isolate the $B$ meson signal: the difference $\Delta E$ between the reconstructed energy of the candidate and the beam energy in the $\Upsilon(4S)$ rest frame.

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*The $B$ meson rest frame is approximated by the $\Upsilon(4S)$ rest frame.*
This distribution follows a sin^2 ground. The same is true for the |K| in the rest frame of the angle of the K using the angle of the B| insensitive to the continuum background. Thus, we require |B| branching fractions for 14 exclusive B meson charmonium decay modes| listed in Table 2. We report, in particular, the first observation of the decay \( B^0 \to \chi_{c1} K^{*0} \to K^+ \pi^- \).

### 3 Electroweak Penguins

Electroweak penguins could be particularly sensitive to the presence of new physics and they could be low energy probes of new phenomena at a much higher energy scale. We present in the following the measurement of the decay \( B \to K^* \gamma \) and a search for the decay \( B^0 \to \gamma \gamma \).

#### 3.1 Decay \( B \to K^* \gamma \)

The decay \( B \to K^* \gamma \) proceeds by the electroweak penguin transition \( b \to s \gamma \). We reconstruct this decay in the mode \( K^* \to K^+ \pi^- \). The radiative photon candidate is found by looking for a cluster in the electromagnetic calorimeter consistent with a photon shower and with an energy between 1.5 and 4.5 GeV in the laboratory, and 2.30 and 2.85 GeV in the center of mass frame. The \( K^+ \) and \( \pi^- \) candidates are identified thanks to the DIRC, an internally-reflecting ring-imaging Cherenkov detector (DIRC), requiring that the cone of light must be consistent with the pion or kaon hypothesis, which leads in a correct \( K/\pi \) assignment in 97% of the cases.

The main background is from continuum \( q\bar{q} \) production with the high-energy photon originating from initial state radiation or from \( \pi^0 \) or \( \eta \) decays. We exploit event topology differences between signal and background to reduce the continuum contribution. The first variable used to achieve that is \( |\cos\Theta^*_T| \), where \( \Theta^*_T \) is the angle, measured in the center of mass frame, between the photon candidate and the thrust vector of the event excluding the B daughter candidates. While the distribution of \( |\cos\Theta^*_T| \) is flat between 0 and 1 for the signal, it is peaked at 1 for the continuum background. Thus, we require \( |\cos\Theta^*_T| < 0.8 \). We further suppress backgrounds using the angle of the B candidate’s direction with respect to the beam axis, \( \Theta^*_B \), and the helicity angle of the \( K^* \) decay, \( \Theta^*_{H} \), defined as the angle between the \( K^+ \) momentum vector computed in the rest frame of the \( K^* \) and the \( K^* \) momentum vector in the parent B meson rest frame. This distribution follows a \( \sin^2\Theta^*_{H} \) distribution for signal and is approximately flat for \( q\bar{q} \) background. The same is true for the B candidate direction with respect to the beam axis. We
require $|\cos \Theta^*_{B}| < 0.80$ and $|\cos \Theta^*_{H}| < 0.75$. The signal is shown in Fig. 3. We find a yield of $139 \pm 13$ events and we derive the branching fraction $B(B^0 \to K^*\gamma) = (4.39 \pm 0.41 \pm 0.27) \cdot 10^{-5}$.

This sample is used to search for $CP$ violating charge asymmetries by constructing $A_{CP} = [(\bar{B} \to \bar{K}^*\gamma) - (B \to K^*\gamma)]/[(\bar{B} \to \bar{K}^*\gamma) + (B \to K^*\gamma)]$. The flavour of the underlying $b$ quark is tagged by the charge of the $K^\pm$ in the decay. We constrain $A_{CP} = -0.035 \pm 0.094 \pm 0.022$.

### 3.2 Decay $B^0 \to \gamma\gamma$

In the Standard Model, the decay $B^0 \to \gamma\gamma$ proceeds via a second order weak transition including gluonic penguinings, followed by annihilation. Standard Model predictions for the branching fraction of these effective flavor-changing neutral current processes range from $0.1$ to $2.3 \cdot 10^{-8}$. Physics beyond the Standard Model could enhance this branching ratio by as much as two orders of magnitude. To look for this decay, we look for events with two isolated photon candidates with energies consistent with photons coming from the decay $B \to \gamma\gamma$. As for the $B \to K^*\gamma$ mode, the main backgrounds are continuum events, and we use similar requirements to eliminate the background. For the purpose of determining number of events and efficiencies, a rectangular signal region in the $(m_{ES}, \Delta E)$ plane is defined. Its size is determined by the $\Delta E$ and $m_{ES}$ resolution. The overall efficiency for $B^0 \to \gamma\gamma$ events, as determined from Monte Carlo simulation, is $(10.7 \pm 0.2)\%$. We find one event in the signal box, with an expected background of $0.9^{+0.4}_{-0.3}$ events. We choose to quote a conservative upper limit on the branching fraction, assuming that the observed event is signal, and set the limit $B(B^0 \to \gamma\gamma) < 2.4 \cdot 10^{-6}$ at the 90% confidence level. This improves the previous limit by a factor twenty.

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