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Inclusive J/ψ production in decays of B mesons

Crystal Ball Collaboration

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Abstract. The production of J/ψ in B meson decays has been measured on the $\Upsilon(4S)$ resonance using the Crystal Ball detector at the e^+e^- storage ring DORIS II. The J/ψ is identified by its e^+e^- decay mode. We obtain a branching ratio of $\mathrm{BR}(B \to J/\psi X) = (1.12 \pm 0.33 \pm 0.25)\%$ in good agreement with theoretical predictions based on color suppression. The J/ψ momentum distribution is observed to be peaked at high values. This implies a substantial contribution from direct B meson decays to the J/ψ. In addition upper limits on J/ψ production in $\Upsilon(1S)$ and $\Upsilon(2S)$ decays and in continuum processes are determined.

1 Introduction

The $\Upsilon(4S)$ resonance decays nearly entirely to a $B\bar{B}$ meson pair, followed by the decay of the B mesons through the weak interaction. In B decay diagrams with a c and $\bar{c}$ quark in the intermediate state these quarks can form charmonium states, see Fig. 1. The detection of such $c\bar{c}$ bound states in decays of B mesons gives information on the influence of the strong interaction in weak decays of heavy mesons. In particular it allows a test of the validity of color suppression because the c and $\bar{c}$ quarks have to match in color. The charmonium states J/ψ and ψ' can be identified by their leptonic decay modes, which have considerable branching ratios. Here we report on a study of J/ψ production in the decay of B mesons produced at the $\Upsilon(4S)$.

The $\Upsilon(1S)$ resonance decays into hadrons mainly via a three-gluon intermediate state. The radially excited state $\Upsilon(2S)$ has in addition hadronic and radiative transitions to the lower lying S and P states of the $b\bar{b}$ system. It is also of importance to search for J/ψ production in $\Upsilon(1S)$ and $\Upsilon(2S)$ decays, and in the continuum below the $\Upsilon(4S)$. Identification of $c\bar{c}$ states there would yield information on the shape of the gluon spectra in decays of the bound resonances and on color rearrangement mechanisms in the final state.

We present an inclusive analysis of J/ψ production, where the J/ψ is observed in its e^+e^- decay mode. Our data have been taken with the Crystal Ball detector from 1982 to 1986 at the e^+e^- storage ring DORIS II at DESY.

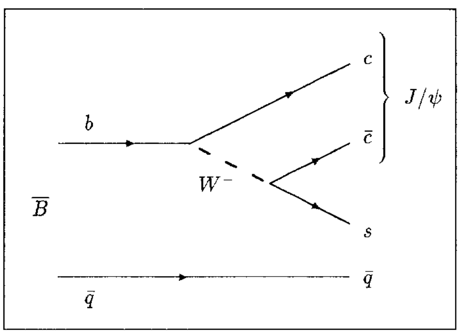

Fig. 1. The color suppressed diagram for J/ψ production in B meson decays

2 Data analysis

A detailed description of the experimental setup can be found in [1, 2]. The principal component of the nonmagnetic Crystal Ball detector is a spherical array of 672 NaI crystals covering 93% of the full solid angle. The detection of charged particles is done by means of a set of cylindrical tube chambers surrounding the beam pipe.

Data have been taken at center-of-mass energies of the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(4S)$ resonance and in the continuum region just below the $\Upsilon(4S)$ between 10.46 GeV and 10.54 GeV. All events used in this analysis satisfy our total energy trigger. It is fully efficient for events depositing at least 1.9 GeV in the NaI crystals which lie within $|\cos\vartheta| < 0.85$, where ϑ is the angle with respect to the beam axix. The integrated luminosity was determined from large angle Bhabha scattering and the QED process $e^+e^- \to \gamma\gamma(\gamma)$.

2.1 Event selection

Multihadron events resulting from e^+e^- collisions are preselected with a set of cuts which rejects events from the main background sources. These cuts are the same as those applied in our analysis of the inclusive electron spectrum from B meson decays [2]. Table 1 summarizes for each of the analyzed samples the integrated luminosity and the number of hadronic events accepted.

In the preselected data samples we search for hadronic events with at least two electron candidates, where the term electron refers to both electrons and positrons. An electron candidate has to leave in the tube chambers a charged track within $|\cos\vartheta| < 0.85$, which points to a region of energy deposition in the NaI. The lateral pattern of this energy deposition has to be consistent with that expected for a single electromagnetically showering particle.

The further analyses of the various samples differ, since different kinematics and background conditions are present. For the $\Upsilon(2S)$ and continuum analyses, no further cuts are applied. The cuts for the $\Upsilon(4S)$ and $\Upsilon(1S)$

Table 1. The integrated luminosities and the numbers of hadronic events of the analyzed data samples. The continuum sample was taken at energies just below the $\Upsilon(4S)$ at $\sqrt{s} = (10.46 - 10.54)$ GeV

	Luminosity $[\mathrm{pb}^{-1}]$	N_{had} $[10^3]$
$\Upsilon(4S)$	88.7	324
$\Upsilon(2S)$	55.6	351
$\Upsilon(1S)$	46.3	575
Continuum	25.9	76

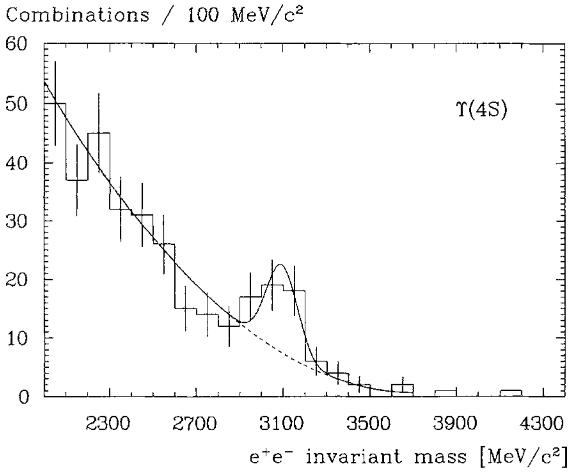

Fig. 2. The di-electron invariant mass spectrum for $\Upsilon(4S)$ data. The solid line represents a fit to the data with a gaussian shape for the J/ψ signal. The width is fixed to the expected detector resolution and the background shape (dashed line) is described by a quadratic polynomial

data samples are described in the following paragraphs. Additional details are given in [3].

The energy spectrum of the selected electrons contains candidates with energies far above the kinematical limit for the decay products of B mesons. This is due to accidentally overlapping energy depositions in the calorimeter and electrons from the process $e^+e^- \rightarrow \tau^+\tau^- \rightarrow eX$. These electron candidates are removed by a cut on the deposited energy of $E \leqq 2.7$ GeV. Since the kinematics of the B decay limits the momentum of the J/ψ to values below 2.0 GeV/c, we restrict the momentum of any di-electron system $p_{ee} \equiv |\mathbf{p}_{e_1} + \mathbf{p}_{e_1}|$ to be less than 2.0 GeV/c.

The $\Upsilon(4S)$ sample contains a large background from continuum processes at $\Upsilon(4S)$ energies. An efficient suppression of this background with small loss of genuine $B\bar{B}$ decays is achieved by a cut on the topology. The Fox-Wolfram moments [4] describe the energy-weighted angular correlation of an event. We define the second Fox-Wolfram moment H_2 as

$$H_2 \equiv \frac{\sum\limits_{ij} E_i E_j (3\cos^2\alpha_{i,j} - 1)}{2(\sum\limits_j E_i)^2}, \qquad (1)$$

where the E_i are the energies of isolated energy clusters in the NaI and $\alpha_{i,j}$ is the angle between the clusters i and j. H_2 has a value close to one for events consisting of two narrow jets and close to zero for almost spherical events. The continuum is predominantly two-jet-like, whereas the $\Upsilon(4S)$ events are more spherical. Therefore we only accept events with a Fox-Wolfram-moment $H_2 \leqq 0.45$.

The di-electron invariant mass distribution for the $\Upsilon(4S)$ analysis is shown in Fig. 2. We observe a signal at the J/ψ mass of 3.1 GeV/c^2. The spectrum is fitted with a Gaussian with a width fixed to our mass resolution of $\sigma_m = 65$ MeV/c^2 (obtained from Monte Carlo sim-

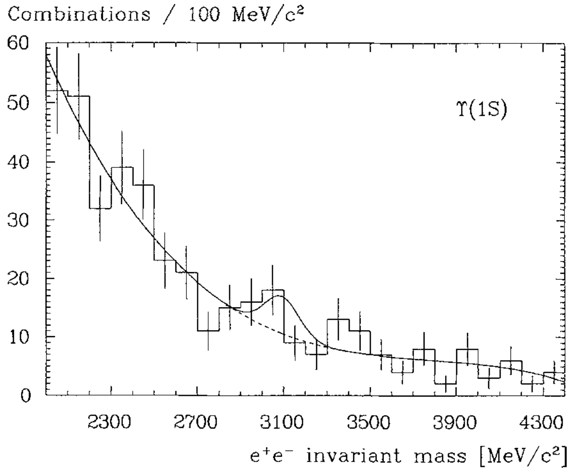

Fig. 3. The di-electron invariant mass spectrum for $\Upsilon(1S)$ data. The fit giving the upper limit for the branching ratio is shown as a solid line. The width of the signal and the J/ψ mass are fixed to the values expected from a Monte Carlo simulation

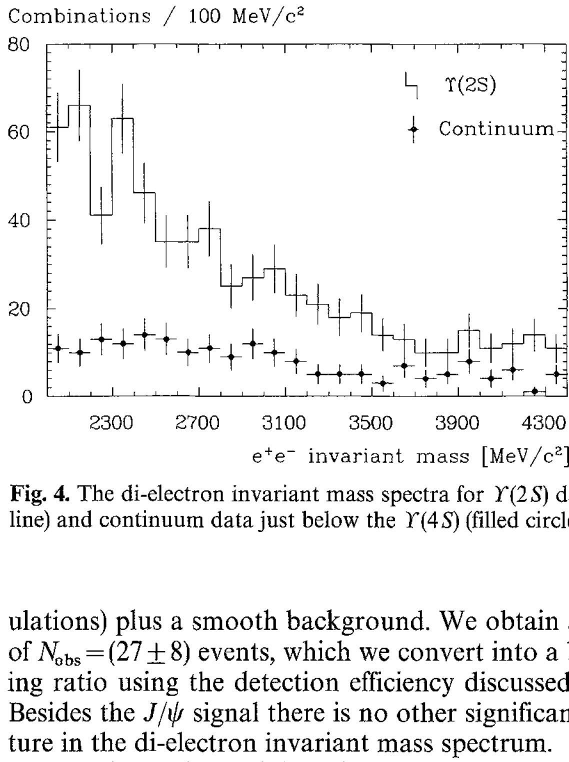

Fig. 4. The di-electron invariant mass spectra for $\Upsilon(2S)$ data (solid line) and continuum data just below the $\Upsilon(4S)$ (filled circles)

ulations) plus a smooth background. We obtain a signal of $N_{\text{obs}} = (27 \pm 8)$ events, which we convert into a branching ratio using the detection efficiency discussed below. Besides the J/ψ signal there is no other significant structure in the di-electron invariant mass spectrum.

For the analysis of the $\Upsilon(1S)$ data we apply different cuts than for the $\Upsilon(4S)$. The cuts are motivated by Monte Carlo studies of $\Upsilon(1S)$ decays into two massless gluons and a J/ψ meson [5]. This simulation shows that the J/ψ meson is preferentially produced with a momentum close to the maximum momentum value of 4.2 GeV/c and that the accompanying hadrons are emitted in the opposite direction. We therefore require for the momentum of any di-electron system $p_{ee} \leqq 4.2$ GeV/c and for the second Fox-Wolfram-moment $H_2 \leqq 0.55$.

The mass spectrum for the $\Upsilon(1S)$ sample is presented in Fig. 3 and for the $\Upsilon(2S)$ and the continuum data in Fig. 4. Neither of these distributions shows a significant signal in the J/ψ mass region. They therefore only yield upper limits on the corresponding branching ratios.

2.2 Background studies

The $\Upsilon(4S)$ data have been further studied to understand the measured shape of the di-electron invariant mass spectrum and to estimate the contributions of individual background reactions. In Fig. 5 the di-electron mass spectrum of the $\Upsilon(4S)$ events is compared with the mass distribution found by combining electron candidates from different $\Upsilon(4S)$ events. The shape of the background is well reproduced in this way. This suggests that the background in the J/ψ signal region originates primarily from combining electron candidates stemming from the semileptonic decays of both B mesons.

Possible background mechanisms which can contribute to the $\Upsilon(4S)$ di-electron sample are:

1. Semileptonic decays of both B mesons:

$$B \to e^+ \nu_e X_1, \quad \bar{B} \to e^- \bar{\nu}_e X_2.$$

2. Semileptonic decays of a B and a $D(D^*)$ meson:

$$B \to \bar{D} e^+ \nu_e X_1$$
$$\quad \llcorner\!\!\longrightarrow e^- \bar{\nu}_e X_2$$
or: $B \to e^+ \nu_e X_1, \ \bar{B} \to D X_2$
$$\quad \llcorner\!\!\longrightarrow e^+ \nu_e X_3.$$

3. Inclusive $D\bar{D}$ production followed by semileptonic decays:

$$e^+e^- \to D\bar{D}X_1, \quad D \to e^+ \nu_e X_2, \quad \bar{D} \to e^- \bar{\nu}_e X_3.$$

4. A hadron misidentified as an electron and an electron from a semileptonic B decay.
5. Two hadrons both misidentified as electrons.

Background from sources 1–5 was studied by simplified Monte Carlo simulations where only the four-vectors of the particles were generated. All particle-particle combinations were formed and the J/ψ mass region was analyzed for the contributions from each of the sources. The detection efficiency for electrons and the misidentification probabilities for hadrons were obtained from a full detector simulation. The results of these studies are summarized in Table 2. It is evident that most of the background in the signal region arises from real di-electron combinations, which cannot be discriminated from those from J/ψ decays. A fit to the di-electron invariant mass spectrum of the $\Upsilon(4S)$ data yields (33.2 ± 9.7) background combinations in the signal region ($m_{J/\psi} \pm 3\sigma_m$).

In addition one might expect a contribution to the J/ψ signal on the $\Upsilon(4S)$ from continuum production of the J/ψ. This background is estimated by applying the selection criteria of our $\Upsilon(4S)$ analysis to the continuum data sample. The resulting di-electron invariant mass spectrum, scaled to the luminosity of the $\Upsilon(4S)$ resonance sample, is shown in Fig. 6. It is seen that the continuum contribution to the background under the J/ψ signal on the $\Upsilon(4S)$ is negligible. Taking into account that part of the continuum background is already esti-

Table 2. The estimated background contributions of the individual background reactions mentioned in the text. The errors quoted are statistical. The overall systematic error is estimated to about $\pm 30\%$. The numbers in the last column have been normalized to give a sum of 100%

Background reaction	# of combinations inside $m^{\text{fit}}_{J/\psi} \pm 3\sigma_m$	Percentage [%]
1. Double semileptonic decay	15.0 ± 1.2	44
2. Parallel/cascade semileptonic decay	5.7 ± 0.6	17
3. $D\bar{D}$ X production	3.0 ± 0.9	9
4. Hadronic fake + semileptonic decay	9.3 ± 1.0	28
5. Two hadronic fakes	0.8 ± 0.1	2
$\sum$	33.8 ± 1.9	100

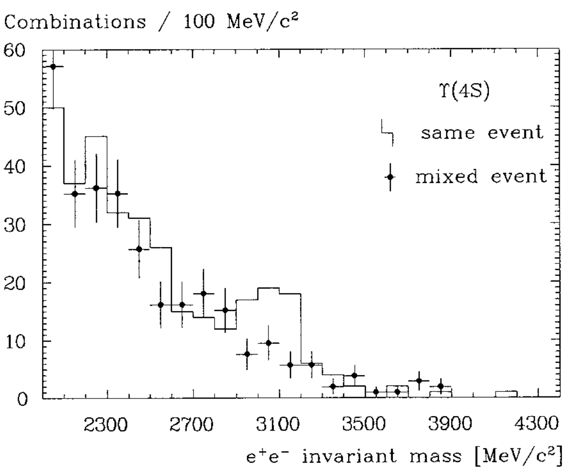

Fig. 5. The invariant mass spectra of electron candidates for electrons of the same event (solid line) and of different events (filled circles). Both distributions are shown for the $\Upsilon(4S)$ resonance data

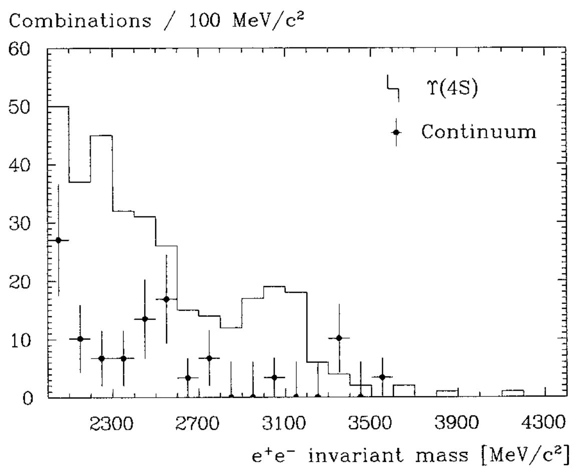

Fig. 6. The invariant mass spectra of electron candidates for $\Upsilon(4S)$ resonance data (solid line) and the continuum data (filled circles) with identical analyses. The distributions are normalized to the same luminosity

mated by the first method (see Table 2), the observed number of background combinations is in reasonable agreement with the sum of the estimated background contributions of the various processes as listed in Table 2. From these studies we conclude that the shape of the background as well as its size is well understood for the $\Upsilon(4S)$ sample.

2.3. *Efficiency calculations*

The detection efficiencies were estimated by Monte Carlo techniques. With the Lund string fragmentation program version 6.2 [6] we simulated the decay chains:

$$\Upsilon(4S) \to B\bar{B}, \quad B_1 \to J/\psi X \to e^+e^- X, \quad B_2 \to \text{anything}$$

and

$$B_1 \to \chi_{c1} X \to J/\psi \gamma X \to e^+e^- \gamma X, \quad B_2 \to \text{anything} \qquad (2)$$

and

$$\Upsilon(1S) \to g g J/\psi \to g g e^+ e^-. \qquad (3)$$

The generated events were passed through a complete detector simulation. Electromagnetically interacting particles were handled by the electromagnetic shower development program EGS 3 [7]. The interaction of hadrons was simulated with the improved GHEISHA 6 program [8, 9]. Extra energy deposited in the crystals by beam-related background was taken into account by adding special background events to the Monte Carlo events. These background events were obtained by triggering on every 10^7th beam crossing with no other condition. The Monte Carlo events were then reconstructed with our standard software and subjected to the same cuts as the real data.

The efficiencies of our data analysis for the specific decay channels mentioned above were obtained by fitting the J/ψ yield in the di-electron invariant mass spectra of the analyzed Monte Carlo event samples. The efficiency is then given by the ratio of the number of reconstructed J/ψ mesons to the number of generated events. The efficiency for the analysis of direct J/ψ production in $\Upsilon(4S)$ decays was determined to be $\varepsilon_{4S} = (24.5 \pm 0.6)\%$, where the error is purely statistical. Since the two considered decay chains for J/ψ production in $\Upsilon(4S)$ decays lead to different J/ψ momentum distributions, we have also calculated the dependence of the efficiency on the J/ψ momentum. Figure 7 shows that the efficiency is essentially flat over the whole J/ψ momentum range.

For the $\Upsilon(1S)$ analysis the efficiency was calculated using events of type (3), yielding $\varepsilon_{1S} = (28.5 \pm 1.3)\%$. No separate physics model was introduced for J/ψ production in $\Upsilon(2S)$ decays. We did not simulate J/ψ production in continuum processes, but estimated the efficiency of the continuum analysis by applying the continuum cuts on the $\Upsilon(1S)$ Monte Carlo sample. The systematic error on ε was enlarged to $\pm 20\%$ to account for this model uncertainty. We thus obtained $\varepsilon_{2S} = \varepsilon_{\text{Cont.}} = (30.7 \pm 1.4)\%$ (statistical error only).

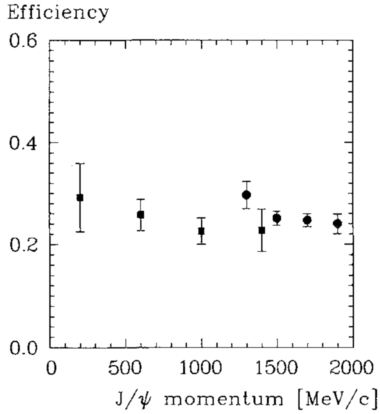

Fig. 7. The efficiency of the analysis of J/ψ production in $\Upsilon(4S)$ decays. The values are the results of a MC simulation for the decay chains: $B \to J/\psi X \to e^+e^- X$ (filled circles) and $B \to \chi_{c1} X \to J/\psi \gamma X \to e^+e^- \gamma X$ (filled squares), respectively

3 Results and discussion

3.1 *Branching ratio*

Assuming that $\Upsilon(4S) \to B\bar{B}$ is the only decay mode of the $\Upsilon(4S)$, the branching ratio for inclusive J/ψ production in B meson decays is given by

$$\text{BR}\,(B \to J/\psi X) = \frac{N_{obs}}{2 N_{B\bar{B}} B_{ee}^{J/\psi} \varepsilon_{4S}}, \qquad (4)$$

where $N_{B\bar{B}}$ denotes the number of produced $B\bar{B}$ meson pairs. This number is given by

$$N_{B\bar{B}} = \frac{1}{\varepsilon_{\text{had}}} \left[N_{\text{had}}(\Upsilon(4S)) - N_{\text{had}}(\text{Cont.}) \frac{L(\Upsilon(4S))}{L(\text{Cont.})} \cdot \left(\frac{E_{\text{beam}}(\text{Cont.})}{E_{\text{beam}}(\Upsilon(4S))} \right)^2 \right], \qquad (5)$$

where ε_{had} denotes the event selection efficiency for hadronic $\Upsilon(4S)$ decays, determined to be $\varepsilon_{\text{had}} = (92.0 \pm 0.9)\%$ (statistical error only). L is the integrated luminosity and N_{had} is the number of observed hadronic events on the $\Upsilon(4S)$ and in the continuum just below the $\Upsilon(4S)$ at beam energies $E_{\text{beam}} = (5.23\text{–}5.27)$ GeV (see Table 1). We obtain $N_{B\bar{B}} = (70.6 \pm 1.5) \cdot 10^3$ events.

Using the branching ratio for the leptonic decay mode of the J/ψ of $B_{ee}^{J/\psi} = (6.9 \pm 0.9)\%$ [10], we obtain:

$$\text{BR}\,(B \to J/\psi X) = (1.12 \pm 0.33 \pm 0.25)\%.$$

The second error is of systematic origin and arises from uncertainties in the determination of $N_{B\bar{B}}$ (2.5%), in the background subtraction by the fit procedure (10%), in the branching ratio for the leptonic decay of the J/ψ (13%) and in the efficiency calculation by Monte Carlo methods (15%). The uncertainty in the efficiency was estimated by varying the selection cuts and changing model assumptions. All contributions were summed in quadrature.

Table 3. The experimental results for inclusive J/ψ production in B meson decays. The numbers of the CLEO analysis have been recalculated using a branching ratio of $(6.9 \pm 0.9)\%$ (instead of $(7.4 \pm 1.2)\%$ for the leptonic decay mode of the J/ψ.) The given weighted average of the branching ratios takes into account the correlated errors from $B_{ee}(J/\psi)$. The given error on the average is obtained by adding statistical and systematic errors in quadrature

Experiment	Decay mode	# of events	Branching ratio for $B \rightarrow J/\psi X$ [%]
CLEO [11]	e^+e^-	29.7 ± 8.4	$1.16 \pm 0.32 \pm 0.31$
	$e^+e^- + \mu^+\mu^-$	82.2 ± 12.4	$1.17 \pm 0.17 \pm 0.19$
CLEO [12]	e^+e^-	87 ± 11	$1.04 \pm 0.14 \pm 0.13$
preliminary	$e^+e^- + \mu^+\mu^-$	207 ± 14	$1.12 \pm 0.10 \pm 0.23$
ARGUS [13]	e^+e^-	63 ± 15	$1.12 \pm 0.26 \pm 0.21$
	$e^+e^- + \mu^+\mu^-$	120 ± 19	$1.07 \pm 0.16 \pm 0.22$
This experiment	e^+e^-	26.8 ± 7.8	$1.12 \pm 0.33 \pm 0.25$
Average			1.12 ± 0.12

J/ψ production has been previously observed by the CLEO [11] [12] and ARGUS [13] collaborations. These experiments have detected the J/ψ through its decays to e^+e^- and $\mu^+\mu^-$. All published results on J/ψ production in B meson decays are summarized in Table 3. There is good agreement among the measurements. The systematic error is largely influenced by the uncertainty of the J/ψ leptonic branching ratio. This error is unfolded from the results before averaging. The systematic error on the average is then dominated by the uncertainty in the J/ψ leptonic branching ratio.

Theoretical predictions for the branching ratio of $B \rightarrow J/\psi X$ cover a wide range from 5% down to values as low as 0.2%. The diagram responsible for this decay is depicted in Fig. 1. In the first approach evaluating this diagram [14], J/ψ formation was assumed to happen for $c\bar{c}$ invariant masses below the $D\bar{D}$ threshold. It was argued that color suppression should be ineffective, leading to a branching ratio of 3% to 5%. More recent calculations included the color selection rules which lowered the predicted branching ratio to 1.5% to 3% [15, 16]. Calculations based on an effective Hamiltonian which considers one-loop gluon corrections to the bare Hamiltonian predict branching ratios of the order 0.2% to 0.5% [16, 17]. Additional uncertainties arise from soft gluon radiation which can partially cancel the color suppression mechanism. A comparison of the experimental results, displaced in Table 3, with the various theoretical models shows that color suppression in the basic weak interaction diagram is needed, but a definite answer about the role of gluons in weak decay processes cannot yet be given by theory.

3.2 Momentum distribution

The momentum distribution of the produced J/ψ mesons in $\Upsilon(4S)$ decays was obtained by applying two different methods. One is based on subtracting the momentum distribution of the sidebands from the one obtained for

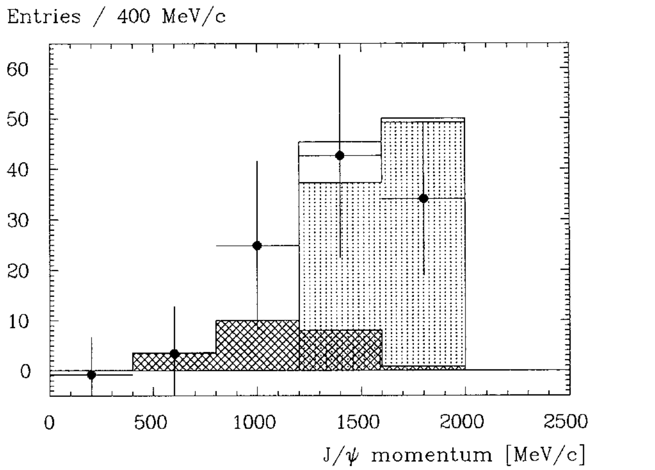

Fig. 8. The measured momentum spectrum (filled circles), background subtracted and efficiency correccted, compared to the Monte Carlo spectrum of primary and secondary produced J/ψ mesons: directly produced (dotted area), via radiative (χ_{c1} or ψ') or hadronic (ψ') transitions (cross hatched area). The sum of both contributions is shown as a solid line

the signal region. The J/ψ signal region is taken as three times the mass resolution σ_m on both sides of the fitted mass peak while the sidebands are defined as the adjacent $3\sigma_m$ wide intervals. The second method is to fit the di-electron invariant mass spectrum in bins of the measured di-lepton momenta p_{ee}. The results obtained by the two methods agree within errors; the acceptance corrected momentum spectrum in Fig. 8 shows the averaged result of the two methods.

The J/ψ momentum distribution can be compared to the distribution from a Monte Carlo simulation of the free quark spectator model $b \rightarrow (c\bar{c})s, (c\bar{c}) = J/\psi, \chi_{c1}, \psi'$. We have assumed that the different $c\bar{c}$ states are produced in the ratio predicted by Kühn et al. [16]:

$$J/\psi : \chi_{c1} : \psi' \approx 1 : 0.27 : 0.31. \tag{6}$$

Using our measured inclusive branching ratio $\mathrm{BR}(B \rightarrow J/\psi X)$ and the radiative and hadronic transition rates in the charmonium system [10], we calculate the expected J/ψ momentum spectrum for each of these processes. Their individual contributions are displayed in Fig. 8 together with their sum. Although this simplified simulation does not include either binding effects of the b quarks inside the B mesons or detector resolution effects, the predicted shape of the momentum spectrum is consistent with the measured distribution. Within the limited statistical accuracy we cannot rule out an additional contribution at low J/ψ momenta as found by Argus [13] and recently by CLEO [12].

3.3 Upper limits

The 90% confidence level (CL) upper limit on the branching ratio is obtained according to [18]:

$$\mathrm{BR}(\Upsilon \rightarrow J/\psi X) \leq \frac{N_{\mathrm{UL}}(1 + 1.28\,\sigma_{\mathrm{rel}})}{N_{\Upsilon}^{\mathrm{prod}}\, B_{ee}^{J/\psi}\, \varepsilon}, \tag{7}$$

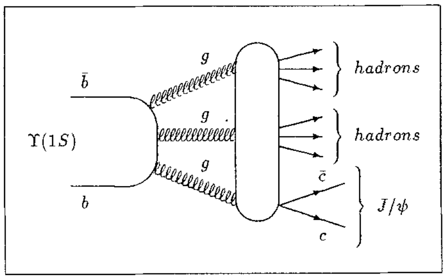

Fig. 9. The diagram for J/ψ production in $\Upsilon(1S)$ decays as proposed in [5]

where N_{UL} denotes the upper limit on the number of observed events at the 90% CL, N_{Υ}^{prod} the number of produced Υ resonance decays and σ_{rel} the relative error of the product $N_{\Upsilon}^{prod} \cdot B_{ee}^{J/\psi} \cdot \varepsilon$. The factor $(1+1.28\sigma_{rel})$ converts this product into an upper limit at the 90% CL.

N_{UL} is determined from log-likelihood fits to the invariant mass spectra. Position and width of the gaussian signals are fixed to the values derived from the Monte Carlo simulation. The background is parametrized by a third order polynomial. The signal area is varied from fit to fit and the normalized log-likelihood fit values are plotted versus the corresponding signal area. This curve is integrated from 0 to N_{UL}, where 90% of the area under the curve is contained in the integral.

There are different mechanisms which can contribute to J/ψ production in decays of the bound Υ resonances. The diagram in Fig. 9 was first proposed by Fritzsch and Streng [5] and later also studied by other groups [19]. One of the gluons in the dominant $3g$ decay of the $\Upsilon(1S)$ can be massive enough to produce a $c\bar{c}$ pair, which can then convert into a colorless $c\bar{c}$ meson by gluon exchange. Streng [20] has estimated a relative decay rate: $\Gamma(\Upsilon \to J/\psi X)/\Gamma(\Upsilon \to \text{hadrons}) \approx (0.2\text{–}0.4)\%$. Also other models could account for J/ψ production, such as gluon fusion processes [21] or the γgg decay of the $\Upsilon(1S)$, but no numerical predictions for the expected branching ratios have been published.

We obtain an upper limit of

$$\mathrm{BR}(\Upsilon(1S) \to J/\psi X) \leqq 0.17\% \quad \text{at the 90\% CL,}$$

which is an order of magnitude improvement over the first limit obtained by the LENA collaboration [22]. Our value is at the lower end of the range predicted by Streng [20]. Recently evidence for J/ψ production in $\Upsilon(1S)$ decays has been reported by the CLEO collaboration [23]. They obtain a branching ratio of 0.11% with a significance of 2.5 standard deviations.

Decay chains which could lead to production of J/ψ in $\Upsilon(2S)$ decays are: direct decay of the $\Upsilon(2S)$ via a $3g$ intermediate state similar to the $\Upsilon(1S)$ process; population of the $\Upsilon(1S)$ through hadronic and radiative transitions from the $\Upsilon(2S)$ with subsequent decay to the J/ψ; radiative transitions to the χ_b levels, which decay through gg or $gq\bar{q}$ intermediate states to charmonium states.

We find an upper limit on J/ψ production in $\Upsilon(2S)$ decays of:

$$\mathrm{BR}(\Upsilon(2S) \to J/\psi X) \leqq 0.6\% \quad \text{at the 90\% CL.}$$

The J/ψ production in hadronic χ_b decays has been estimated in [5] to be about 1% of the hadronic decays of the $^3P_{0,2}$ states of the $b\bar{b}$ system. After taking into account the branching ratios for the radiative transitions of the $\Upsilon(2S)$ to the ^3P states which are of the order (4–7)% [10], this predicted branching ratio is far below our upper limit.

The production of charmonium states in e^+e^- continuum annihilation is estimated within various models [24–26]. The corresponding production cross sections are expressed in terms of an R value, which gives the J/ψ continuum production cross section in units of the Born cross section for muon pair production $e^+e^- \to \mu^+\mu^-$. At center-of-mass energies around 10 GeV, the expected R values are in the range $(0.2\text{–}1)\cdot 10^{-3}$ depending on the model applied. The models also differ in their predictions for the momentum spectra and the angular distributions of the J/ψ mesons.

We obtain an upper limit at the 90% CL of

$$R_{J/\psi} \leqq 0.03 \quad \text{at } \sqrt{s} = 10.49\ \text{GeV},$$

where the quoted center-of-mass energy represents the luminosity-weighted mean of the continuum data sample. This upper limit corresponds to less than $6 \cdot 10^{-3}$ J/ψ mesons per hadronic continuum event.

Continuum production of J/ψ mesons has also been searched for by the PLUTO [27] and the CLEO [11] collaboration at $\sqrt{s} = (4\text{–}10)$ GeV without evidence. The CLEO group has obtained a stringent upper limit of $R_{J/\psi} \leqq 4.2 \cdot 10^{-3}$ at $\sqrt{s} \approx 10$ GeV. However, even this limit is unable to distinguish between the different models at these center-of-mass energies. Only the measurements made at $\sqrt{s} \approx 30$ GeV [28, 29] exclude the mechanism proposed by Kane et al. [25].

4 Conclusions

We have searched for the charmonium state J/ψ in decays of Υ resonances. Our results can be summarized as follows: J/ψ production in the decays of B mesons has been observed with a branching ratio of $\mathrm{BR}(B \to J/\psi X) = (1.12 \pm 0.33 \pm 0.25)\%$. Our result is in good agreement with other experiments and disfavors models which do not include color suppression. A hard momentum distribution is observed for the produced J/ψ mesons; this supports models which predict a dominant direct production of J/ψ. We see no evidence for J/ψ production in $\Upsilon(1S)$ and $\Upsilon(2S)$ decays and in the continuum just below the $\Upsilon(4S)$ and place upper limits on the corresponding branching ratios.

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