Production of J/ψ Mesons from χ_c Meson Decays in $p\overline{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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 0031-9007/97/79(4)/578(6)$10.00

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(Received 7 February 1997)

We have measured the fraction of J/ψ mesons originating from χ_c meson decays in $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV. The fraction, for $P_T^{J/\psi} > 4.0$ GeV$/c$ and $|\eta^{J/\psi}| < 0.6$, not including contributions from b flavored hadrons, is 29.7% $\pm$ 1.7%(stat) $\pm$ 5.7%(syst). We have determined the cross sections for J/ψ mesons originating from χ_c decays and for directly produced J/ψ mesons. We have found that direct J/ψ production is in excess of the prediction of the color singlet model by the same factor found for direct $\psi(2S)$ production. [S0031-9007(97)03615-6]

PACS numbers: 13.85.Ni, 14.40.Gx

In $p\overline{p}$ collisions charmonium particles come from prompt production and from the decay of b flavored hadrons. Calculations based on the color singlet model (CSM) for prompt production predict that the yield of J/ψ mesons not coming from the decay of heavier charmonium states (direct production) is suppressed, and χ_c mesons are expected to be the main source (>90%) of prompt J/ψ's. The observed yields of prompt J/ψ and $\psi(2S)$ mesons are larger than the theoretical expectation by factors of about 6 and 50, respectively [1]. This discrepancy, especially for the $\psi(2S)$, has suggested that other important mechanisms exist for direct production of charmonium $^3S_1$ states at large P_T, beyond those considered in the CSM [2–4]. It is therefore important to account separately for all charmonium states produced and understand whether the disagreement of the theory with data is confined to the $\psi(2S)$ or an excess of direct production shows up also for the J/ψ.

In this Letter we report the results of a study of the reaction $p\overline{p} \to \chi_c X$, $\chi_c \to J/\psi\gamma$, $J/\psi \to \mu^+\mu^-$ at $\sqrt{s} = 1.8$ TeV using the Collider Detector at Fermilab (CDF). Since the branching fractions for χ_c decays into other modes containing a J/ψ are expected to be small this study yields the fraction of J/ψ from χ_c. This measurement is based on 18 pb^{-1} of data collected in the 1992–1993 collider run, and is the first where the contribution from b decays to χ_c production is measured. This study allows us to disentangle direct J/ψ production from the contribution due to χ_c decays in promptly produced charmonia, and to compare the measured cross sections with the theoretical predictions separately for the direct and χ_c contributions.

The CDF detector has been described in detail elsewhere [5]. The events used in this analysis were collected with the dimuon trigger described in [1]. A J/ψ is identified by requiring two oppositely charged muon candidates both with $P_T > 2.0$ GeV/c and at least one with $P_T > 2.8$ GeV/c. The muon pair is required to have $P_T(\mu^+\mu^-) > 4.0$ GeV/c and $|\eta(\mu^+\mu^-)| < 0.6$ and is considered a J/ψ candidate if its invariant mass is in the region 3057 MeV/$c^2 < M(\mu^+\mu^-) <$ 3137 MeV/c^2. This selection yields a sample of 34 367 J/ψ candidates, where the estimated number of real J/ψ mesons is 32 642 ± 185. In this sample we select photon candidates by demanding an energy deposition of at least 1 GeV in a cell of the central electromagnetic calorimeter and a signal in the fiducial volume of the strip chambers (CES), embedded in the calorimeter at a depth of six radiation lengths. The cell is 15° wide in ϕ, 0.1 wide in η, and fully contains the shower. We also require that no charged particles point to the photon candidate cell (the no-track cut). The location of the signal in the CES chambers and the event interaction point determine the direction of the photon momentum; its magnitude is the energy deposited in the calorimeter. The J/ψ is combined with all photon candidates in the event and the invariant mass difference, $\Delta M = M(\mu^+\mu^-\gamma) - M(\mu^+\mu^-)$, is calculated. The ΔM distribution is shown in Fig. 1(a). A clear signal is present near $\Delta M = 400$ MeV/c^2 as expected from χ_c decays, but the individual χ_{c1} and χ_{c2} states are not resolved. The mass resolution of 50 (55) MeV/c^2, predicted by a detector simulation for the χ_{c1} (χ_{c2}), is insufficient to resolve the two states which are separated by 45.6 MeV/c^2.

The shape of the background resulting from combinations of the J/ψ with photons of the underlying event is obtained with a Monte Carlo method that uses J/ψ candidate events as input. Photons come primarily from the decay of π^0, η, and K_S^0. These sources are simulated replacing each charged particle in the event, other than the two muons, by a π^0, η, or K_S^0 with probabilities proportional to 4:2:1. These proportions follow from isospin symmetry and the ratios $K^\pm/\pi^\pm = 0.25$, $\eta/\pi^0 = 0.5$ [6]. Uncertainties in these ratios, and the effect of physics processes resulting in a J/ψ associated with photons in the final state, are considered as sources of systematic uncertainty. The response of the detector to the photons resulting from the decay of these embedded neutral particles is calculated using a Monte Carlo simulation. Applying

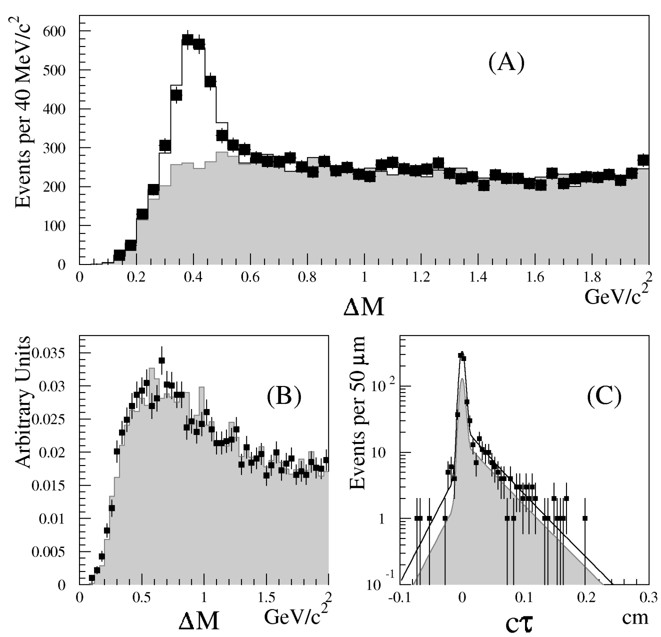

FIG. 1. (a) The mass difference (ΔM) distribution after the selection described in the text. The points represent the data. The shaded histogram is the background shape predicted by the Monte Carlo calculation. The solid line is the fit of the data to a Gaussian function plus the background histogram. (b) The comparison between the ΔM distribution for dimuons in the J/ψ sidebands, and the corresponding one predicted by the Monte Carlo calculation; the two distributions are normalized to equal area and the vertical scale is arbitrary. (c) The proper lifetime distribution, for the subset of $J/\psi\gamma$ combinations in the χ_c signal region, when the muons have silicon vertex detector (SVX) information. The points represent the data. The shaded area is the background contribution.

the χ_c reconstruction to these events results in a mass distribution that models the shape of the background. This model was tested by comparing the Monte Carlo distribution with that directly obtained from the data for dimuon pairs in the mass sidebands of the J/ψ peak where there should be no χ_c signal. The two distributions agree well as shown in Fig. 1(b). The number of χ_c signal events is determined by fitting the data ΔM distribution to the sum of the background distribution, with an unconstrained normalization, and a Gaussian function associated with the signal. This results in 1230 $\pm$ 72 χ_c signal events for the distribution shown in Fig. 1(a).

We determine the rate of J/ψ and χ_c mesons in the four subsamples (bins) defined by $4 < P_T^{J/\psi} < 6$, $6 < P_T^{J/\psi} < 8$, $8 < P_T^{J/\psi} < 10$, and $P_T^{J/\psi} > 10$ GeV/c. The fraction of J/ψ from χ_c decays is calculated according to the equation

$$F_\chi^{J/\psi} = \frac{N^{\chi_c}}{N^{J/\psi} A_{J/\psi}^\gamma \epsilon_{\mathrm{trk}}^\gamma \epsilon_{\mathrm{env}}^\gamma},$$

where N^{χ_c} and $N^{J/\psi}$ are the numbers of reconstructed χ_c and J/ψ mesons, respectively, $A_{J/\psi}^\gamma$ is the probability to reconstruct the photon once the J/ψ is found, $\epsilon_{\mathrm{trk}}^\gamma$ is the efficiency of the no-track cut, and $\epsilon_{\mathrm{env}}^\gamma$ is the efficiency to reconstruct the photon in the presence of additional energy deposited in the calorimeter.

The photon acceptance, $A_{J/\psi}^\gamma$, is the product of the probability that the photon is within the fiducial volume, and the reconstruction efficiency of the fiducial photon. The geometric acceptance is determined by using a Monte Carlo simulation. The χ_c's are generated uniformly in η, and with a P_T distribution tuned to reproduce the observed rate of χ_c's as a function of $P_T^{J/\psi}$. The $\chi_c \to J/\psi\gamma$ decay is generated with a uniform angular distribution in the χ_c rest frame. The $J/\psi \to \mu^+\mu^-$ decay is also generated uniformly in the J/ψ rest frame and the trigger simulation is applied to the decay muons. The unknown χ_c polarization is considered as a source of systematic uncertainty. The photon reconstruction efficiency is obtained from real data by applying the photon requirements, except for the no-track cut, to a sample of electrons from photon conversions selected using only tracking information. This efficiency is then corrected for the differences in detector response between photons and electrons. For $P_T^{J/\psi} > 4.0$ GeV/c, the photon acceptance is 0.146 $\pm$ 0.002(stat).

To study the effect of the no-track cut, and the effect of additional energy deposited in the calorimeter, we use a sample of $\chi_c \to J/\psi\gamma$ reconstructed by requiring the decay photon to convert into an electron-positron pair. The resulting sample of 26 $\pm$ 5 χ_c's is unbiased with respect to the no-track cut and calorimetric requirements. The effect of these can be determined by measuring the track multiplicity and energy distribution associated with the calorimeter cell, which would have been hit by the photon had it not converted. The mean multiplicity of nonmuon tracks pointing to this cell has a value of 0.08 $\pm$ 0.06, and the efficiency of the no-track cut is $\epsilon_{\mathrm{trk}}^\gamma = (97.9^{+2}_{-5})\%$. The energy distribution in the same cell, when there are no tracks pointing to it, has a mean value of (0.15 $\pm$ 0.08) GeV. The effect of this energy deposition on our photon reconstruction is accounted for by an "environmental" efficiency of $\epsilon_{\mathrm{env}}^\gamma = (96.5^{+3.5}_{-4.5})\%$.

The systematic uncertainty on $F_\chi^{J/\psi}$ associated with the reconstruction efficiency of the low energy photon is $\pm 10\%$. This is due to uncertainties in the estimation of the detector response difference between photons and electrons. A $\pm 11\%$ uncertainty is associated with the χ_c production and decay model used for the acceptance calculation. This is estimated upon variations of the shape of the P_T spectrum as well as the decay angular distribution to account for fully polarized χ_c. The uncertainty in the determination of N^{χ_c} associated with the model of the background shape is $\pm 10\%$. This includes the effect of varying the fitted normalization of the background contribution by $\pm 1\sigma$; varying the π^0, η, and K_S^0 composition in our background model from 4:2:1 to equal amounts of π^0 and K_S^0, and to all π^0; and includes the effect of physics processes resulting in a J/ψ associated with photons in the final state. An additional $\pm 6\%$ uncertainty arises from the statistical and systematic uncertainties associated with $\epsilon_{\mathrm{trk}}^\gamma$ and $\epsilon_{\mathrm{env}}^\gamma$. We combine these uncertainties, assuming they are independent, in a total systematic uncertainty of $\pm 18.9\%$ correlated in the four bins. The fraction of J/ψ mesons coming from χ_c decays is $F_\chi^{J/\psi} = 27.4\% \pm 1.6\%(\mathrm{stat}) \pm 5.2\%(\mathrm{syst})$ for $P_T^{J/\psi} > 4$ GeV/c and $|\eta^{J/\psi}| < 0.6$.

This fraction includes a contribution from b decays. The fraction of J/ψ mesons from χ_c decays not including contributions from b decays is calculated according to the equation

$$F(\not b)_\chi^{J/\psi} = \frac{N^{\chi_c} - N_b^{\chi_c}}{(N^{J/\psi} - N_b^{J/\psi}) A_{J/\psi}^\gamma \epsilon_{\mathrm{trk}}^\gamma \epsilon_{\mathrm{env}}^\gamma} = F_\chi^{J/\psi} \frac{1 - F_b^\chi}{1 - F_b^{J/\psi}},$$

where $N_b^{\chi_c}$ and $N_b^{J/\psi}$ are the numbers of reconstructed χ_c and J/ψ mesons from b's, F_b^χ and $F_b^{J/\psi}$ are, respectively, the fractions of reconstructed χ_c and J/ψ mesons from b's.

To measure F_b^χ we use a sample of 555 $\pm$ 47 reconstructed χ_c, where both muon tracks have information in the SVX. We constrain the two muons to come from a common decay vertex and we calculate L_{xy}, the projection of the decay length onto the transverse momentum vector of the J/ψ. To account for the difference between the Lorentz boost $\beta\gamma$ of the parent b hadron and that of the observed J/ψ, we convert L_{xy} into a proper lifetime using $\beta\gamma$ of the J/ψ, and a correction factor $F_{\rm corr}$ determined from Monte Carlo: $c\tau = L_{xy}(M^{J/\psi}/P_T^{J/\psi})/F_{\rm corr}$ [7]. We fit the $c\tau$ distribution to the sum of two functions, one associated with the χ_c signal and one associated with its background. Each function is the sum of a zero lifetime component, described by a Gaussian plus symmetric exponential tails, and a long lived component, described by a positive exponential smeared with a Gaussian resolution function. The background component is derived from the Monte Carlo described previously and normalized to the estimated background under the χ_c signal. The $c\tau$ distribution is shown in Fig. 1(c). The fit yields $F_b^\chi = 10.8\% \pm 3.1\%$, where we have fixed the lifetime of the long lived component to the average b lifetime of 438 μm [7]. Using the method described in [1] we find $F_b^{J/\psi} = 17.8\% \pm 0.45\%$ for $P_T^{J/\psi} > 4.0$ GeV$/c$. The resulting correction factor is $(1 - F_b^\chi)/(1 - F_b^{J/\psi}) = 1.085 \pm 0.037$. A Monte Carlo calculation shows that this factor is independent of $P_T^{J/\psi}$. Therefore we use this correction for all P_T bins. We have also measured $\epsilon_{\rm trk}^\gamma$ and $\epsilon_{\rm env}^\gamma$ using a sample of prompt $\chi_c \to J/\psi\gamma$, $\gamma \to e^+e^-$, requiring $|L_{xy}| <$ 100 μm. The efficiencies for prompt χ_c are consistent with the values obtained previously. The uncertainties on $F_b^{J/\psi}$ and F_b^χ increase the total systematic uncertainty on $F(\not b)_\chi^{J/\psi}$ to 19.2%. The resulting fraction of J/ψ mesons from χ_c decays, not including contributions from b's, is $F(\not b)_\chi^{J/\psi} = 29.7\% \pm 1.7\%$(stat) $\pm$ 5.7%(syst) and is shown as a function of $P_T^{J/\psi}$ in Fig. 2.

To obtain the direct J/ψ cross section, we subtract from the prompt J/ψ cross section [1] the contribution from χ_c and $\psi(2S)$ decays. The first is obtained by multiplying the prompt J/ψ cross section with a parametrization of $F(\not b)_\chi^{J/\psi}$ as a function of $P_T^{J/\psi}$. The second is calculated from the prompt $\psi(2S)$ cross section measured in [1] and a Monte Carlo simulation of the decays $\psi(2S) \to J/\psi X$, where $X = \pi\pi$, η, π^0. With this calculation we find that the fraction of prompt J/ψ's from $\psi(2S)$'s rises from 7% $\pm$ 2% at $P_T^{J/\psi} = 5$ GeV$/c$ to 15% $\pm$ 5% at $P_T^{J/\psi} =$ 18 GeV$/c$. The fraction of directly produced J/ψ's is 64% $\pm$ 6% and is approximately independent of $P_T^{J/\psi}$ between 5 and 18 GeV$/c$. Direct production is therefore the largest source of prompt J/ψ mesons. The resulting cross sections are shown in Fig. 3. The curves correspond to the theoretical predictions [8]. The calculation of the direct J/ψ cross section (dashed line) is below the experimental measurement by a factor of 80 at $P_T^{J/\psi} = 5$ GeV$/c$, and by a factor of 30 at $P_T^{J/\psi} = 18$ GeV$/c$. The solid curve in Fig. 3 includes contributions from the CSM and the color octet model (COM), where the color octet contribution is based on early extractions [9] of the relevant nonperturbative parameters from the branching ratios of $b \to \chi_c X$ decays. The extension of the COM to the $^3S_1$ states has been proposed in [3]; the corresponding calculations have been compared in [4] with our preliminary data showing that agreement between theory and data can be obtained by adjusting the nonperturbative parameters introduced in the COM.

In conclusion, we have measured the fraction of J/ψ's originating from χ_c's and found that the majority of prompt J/ψ's do not come from χ_c's but are directly produced. We have compared the data with the prediction of the CSM and found that this model underestimates direct J/ψ production by a factor varying from 80 to 30.

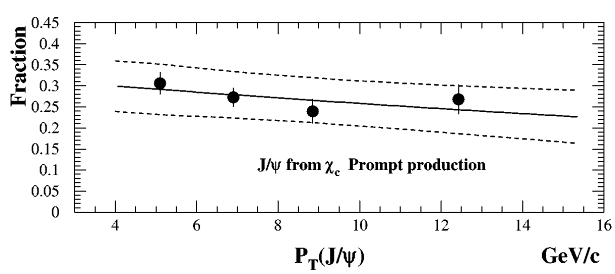

FIG. 2. The fraction of J/ψ mesons from χ_c decays as a function of $P_T^{J/\psi}$ with the contribution from b's removed. The error bars correspond to the statistical uncertainty. The solid line is the parametrization of the fraction. The dashed lines show the upper and lower bounds corresponding to the statistical and systematic uncertainties combined.

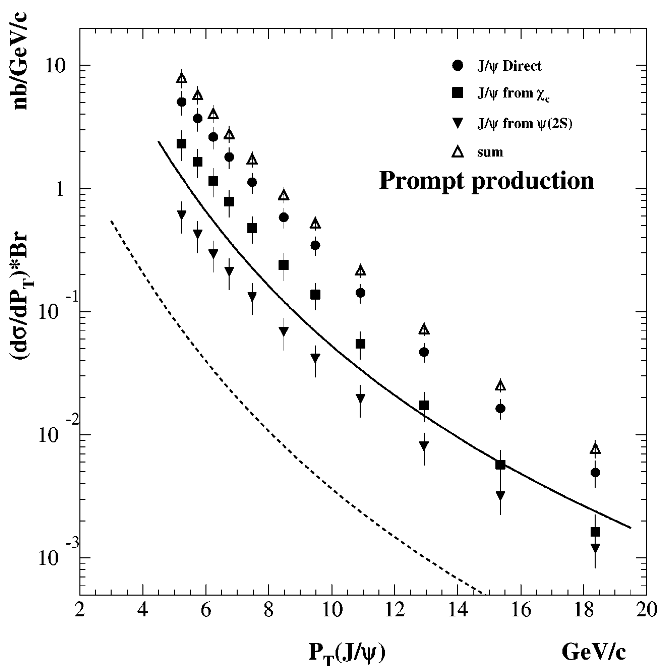

FIG. 3. The differential cross sections of prompt $J/\psi \to \mu^+\mu^-$ as a function of $P_T^{J/\psi}$. The dashed curve is the color singlet calculation for J/ψ production. The solid curve is the calculation of $\chi_c \to J/\psi\gamma$ production and includes both color singlet and color octet contributions. The error bars correspond to the statistical and systematic uncertainties combined and include the uncertainties common to all data points.

This factor is of the same order as the one found in [1] for the $\psi(2S)$. We conclude that the CSM fails to describe direct production of both the J/ψ and the $\psi(2S)$ by about the same factor.

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation, the Italian Istituto Nazionale di Fisica Nucleare, the Ministry of Education, Science and Culture of Japan, the Natural Sciences and Engineering Research Council of Canada, the National Science Council of the Republic of China, and the A. P. Sloan Foundation.

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