Production of J/ψ at Large x_F in 800 GeV/c p-Copper and p-Beryllium Collisions

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The differential cross sections $d\sigma/dx_F$ for J/ψ produced inclusively in 800 GeV/c p-Cu and p-Be collisions have been measured in the kinematic range $0.30 \leq x_F \leq 0.95$ through the decay mode $J/\psi \to \mu^+\mu^-$. They are compared with the predictions of the semilocal duality model for several sets of parton density functions. No evidence for a suggested intrinsic charm contribution to the cross section is observed. The ratio of the differential cross sections for Cu and Be targets confirms the suppression of J/ψ production in heavy nuclei at large x_F.

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Hadronic production of J/ψ can serve as a test of quantum chromodynamics (QCD) and the parton model of hadronic structure. At the scale $Q^2 = m_{J/\psi}^2$, the strong coupling constant α_s is small enough (≈ 0.2–0.3) to apply QCD perturbatively. To lowest order in α_s there are two leading processes for charm quark production, gluon-gluon fusion and quark-antiquark annihilation. While gluon-gluon fusion is predicted to dominate the total cross section, quark-antiquark annihilation should be important at large values of Feynman x ($x_F \gtrsim 0.6$). When the transverse momentum $p_\perp$ is small compared with the J/ψ mass, the cross section for J/ψ production can be calculated by convolving the QCD cross sections with the parton density functions, according to the semilocal duality model [1]. The intrinsic charm model [2] predicts an additional contribution to J/ψ production at large x_F due to $c\bar{c}$ fluctuations in the incident proton that carry a large fraction of the beam momentum during their brief existence. Experimentally, J/ψ production at large x_F (corresponding to small values of x_2, the momentum fraction carried by partons in the target nucleon) has not been thoroughly explored in high energy proton-induced reactions.

In hadron-nucleus collisions, J/ψ production is seen to be suppressed in heavy nuclei compared to light nuclei [3]. The intrinsic charm model, among others, provides a mechanism for such a suppression by enhancing the absolute yield of J/ψ with large x_F in light relative to heavy nuclei due to an A dependence different from that of parton fusion.

Using the E605/E789 spectrometer at Fermilab [4,5], we have measured the differential production cross section of J/ψ with 800 GeV/c protons on copper and beryllium, with good acceptance for $p_\perp < 5$ GeV/c over the kinematic range $0.30 < x_F < 0.95$. A primary beam of 10^{10} protons per 20 sec spill was stopped by a 4.27 m long copper beam dump suspended midway through a 14 m long magnet (SM12). Most primary protons interacted

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in the first few interaction lengths of the dump. J/ψ events produced in the beam dump were observed via the decay $J/\psi \to \mu^+\mu^-$. For a portion of the data, a thick beryllium target (91.4 cm long) was added in front of the dump to study the nuclear dependence of J/ψ production. The momentum of the tracks was measured by a 3.4 m long analysis magnet (SM3) which delivered a nearly uniform transverse momentum kick of 0.91 GeV/c. The spectrometer consisted of three stations of hodoscopes and drift chambers for triggering and tracking. Two hodoscope planes and three proportional tube planes, located behind the calorimeters and a thick hadron absorber, formed the fourth station of detectors and were used for muon identification and triggering. The hodoscopes were divided into left, right, up, and down sectors.

Two complementary triggers were employed to look for dimuon pairs. These two triggers in combination were used to measure hodoscope efficiencies. The different trigger acceptances also provided a systematic check of the Monte Carlo simulation [5].

Reconstructed tracks were required to have hits in at least 14 of 18 drift chamber planes, a fit quality of $\chi^2/N_{\rm DF} < 5$, a momentum between 20 and 800 GeV/c, and to have fired at least 3 out of 5 hodoscopes in the first three stations within appropriate fiducial areas. A track was identified as a muon if there were at least three hits associated with it in the station 4 detectors within windows centered on the projections of the track from stations 1-3. The efficiency of the muon identification was measured to be better than 99%.

Only events with two oppositely charged muons were considered for further analysis. Like-sign muon pairs and three-muon events accounted for 4% of all reconstructed events. Tracks were traced to the beam dump using detailed SM12 and SM3 field maps. The tracks were required to trace back through at least 1 m of copper in the dump and to intercept the nominal target plane, $Z_{\rm tgt}$, within 3 standard deviations from the beam centroid. $Z_{\rm tgt}$ was defined as the position corresponding to one interaction length into the dump or Be target.

In the traceback procedure, corrections were made for the effects of energy loss and multiple scattering in the dump material [6]. To correct for the effects of multiple scattering, an angular correction to the track direction, calculated at an effective scattering plane located near the downstream end of the dump, was made so that the track would trace back to the beam centroid at $Z_{\rm tgt}$. The effect of this correction was to reduce the rms width of the J/ψ mass peak from ≈ 400 MeV/c^2 to ≈ 270 MeV/c^2. The resulting dimuon invariant mass distributions display a clear J/ψ peak, as shown in Fig. 1. Monte Carlo studies demonstrate that the traceback procedure does not bias the reconstructed mass, and reproduces the input x_F distribution values to better than 1% with an rms resolution in x_F varying from 0.006 to 0.02 as x_F increases from 0.325 to 0.925.

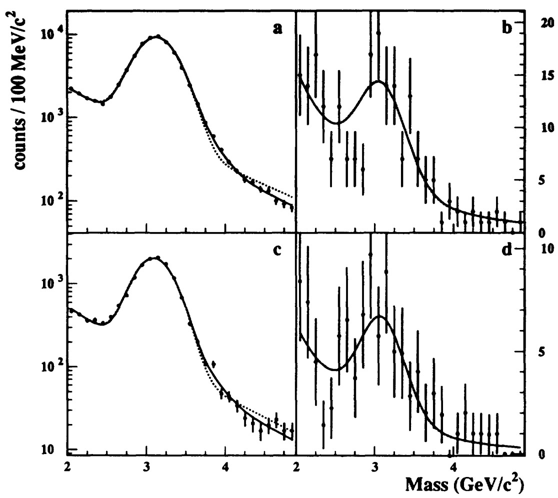

FIG. 1. Dimuon mass distributions for the copper dump (a),(b) and beryllium target (c),(d). Plots (a) and (c) show the interval $0.30 \leq x_F < 0.35$ while (b) and (d) show $0.85 \leq x_F < 0.90$. Note that (a) and (c) are shown with semilog scale, while (b) and (d) are linear. The dotted curves fit with the J/ψ only, while the solid curves include both the J/ψ and ψ'.

To extract the J/ψ yield as a function of x_F, maximum-likelihood fits were performed to the dimuon invariant mass spectrum for each x_F bin in the region $2.0 < M_{\mu\mu} < 5.0$ GeV/c^2 [7]. The fits included a continuum parametrized as $M_{\mu\mu}^{-1}\exp(a+bM_{\mu\mu})$ and one or two Gaussians fixed at the known J/ψ and ψ' masses, with widths increasing linearly with x_F (consistent with both the data and Monte Carlo studies). As shown in Fig. 1, the two-Gaussian fit is preferred over most of the x_F range. For the copper data, at x_F of 0.325, the difference in log-likelihood between the two fits was 64 units; this is equivalent to an 11 standard deviation improvement. For $0.30 \leq x_F \leq 0.95$, the ratio $B\,d\sigma/dx_F(\psi')/B\,d\sigma/dx_F(J/\psi)$ remained constant, with a mean of 0.0133 ± 0.0005, similar to observations at lower energies in pion [8] and proton collisions [9]. In the final analysis this ratio was held constant. Summing over $x_F > 0.3$, 2.0×10^5 J/ψ events were observed in the copper data and 4.5×10^4 with beryllium.

The per-nucleus differential cross section $d\sigma/dx_F$ is given by

$$\frac{d\sigma}{dx_F} = \frac{N_{\rm obs}}{N_B \epsilon l B \Delta x_F}\sigma_I\,, \qquad (1)$$

where $N_{\rm obs}$ is the number of $J/\psi \to \mu^+\mu^-$ events observed in a given x_F bin, N_B is the number of interacting beam protons, ϵ is the overall (acceptance $\times$ trigger $\times$ reconstruction) efficiency determined by Monte Carlo studies, l is the live time (typically > 0.85), $B = (5.97 \pm 0.25)\times 10^{-2}$ is the branching ratio for $J/\psi \to \mu^+\mu^-$ [10], $\Delta x_F = 0.05$ is the bin width in x_F, and σ_I, taken to be 782 ± 23 mb for copper and 199 ± 5.8 mb for

TABLE I. Differential cross sections $(1/A)d\sigma/dx_F(p+A \to J/\psi)$ for copper and beryllium. The first error is statistical and the second is the diagonal element of the systematic covariance (see text). An overall normalization uncertainty of 12% is not included.

x_F Bin	$(1/A)d\sigma/dx_F$ (nb/nucleon) Cu	Be
0.325	$211.3 \pm 0.7 \pm 9$	$241 \pm 2 \pm 9$
0.375	$121.0 \pm 0.4 + -2$	$138 \pm 1 \pm 3$
0.425	$70.2 \pm 0.3 \pm 1$	$83.2 \pm 0.8 \pm 1$
0.475	$40.9 \pm 0.2 \pm 0.7$	$49.4 \pm 0.6 \pm 0.8$
0.525	$23.4 \pm 0.2 \pm 0.3$	$28.0 \pm 0.4 \pm 0.5$
0.575	$12.7 \pm 0.1 \pm 0.2$	$16.1 \pm 0.3 \pm 0.3$
0.625	$6.57 \pm 0.08 \pm 0.09$	$8.4 \pm 0.2 \pm 0.2$
0.675	$3.27 \pm 0.06 \pm 0.06$	$3.9 \pm 0.2 \pm 0.2$
0.725	$1.39 \pm 0.04 \pm 0.04$	$2.0 \pm 0.1 \pm 0.1$
0.775	$0.54 \pm 0.02 \pm 0.03$	$0.66 \pm 0.06 \pm 0.06$
0.825	$0.22 \pm 0.01 \pm 0.01$	$0.20 \pm 0.03 \pm 0.03$
0.875	$0.057 \pm 0.008 \pm 0.008$	$0.13 \pm 0.02 \pm 0.03$
0.925	$0.016 \pm 0.006 \pm 0.005$	< 0.028 (95% C.L.)

beryllium [10,11], is the total inelastic cross section for 800 GeV/c protons. For the beryllium data, an additional correction was made to account for the fraction of incident protons, estimated to be 0.106 ± 0.004, passing through the beryllium target without interacting. The resulting differential cross sections for J/ψ production in p-Cu and p-Be collisions at $\sqrt{s} = 38.7$ GeV are given in Table I and plotted in Fig. 2. Because of the correlation between the relative systematic errors, only the statistical uncertainties are plotted.

The absolute normalization uncertainty, estimated to be $\pm 12\%$ for both the copper and beryllium results, was dominated by the calibration error of the beam monitor. The next largest contribution came from the uncertainty in the branching ratio for $J/\psi \to \mu^+\mu^-$, followed by the uncertainties in the inelastic cross sections. We estimated the systematic uncertainty in the relative normalization ratio between copper and beryllium to be $\pm 5\%$. The systematic covariance in the overall efficiency was examined with Monte Carlo studies [5], in which the magnetic fields, the $p_\perp$ [12], and decay angular distributions of the J/ψ [13] were varied by 1 standard deviation.

The shape of the differential cross section is often parametrized as $d\sigma/dx_F \propto (1 - x_F)^n$. With both statistical and systematic covariances taken into account, in the region $0.30 < x_F < 0.95$, the best fit exponent is $n = 5.21 \pm 0.04$ with $\chi^2/N_{\rm DF} = 20$ for copper, and $n = 5.32 \pm 0.05$ with $\chi^2/N_{\rm DF} = 7$ for beryllium, both poor fits.

We have compared our results with the predictions of the semilocal duality model [1]. Here the absolute normalization and the charm-quark mass m_c are the only adjustable parameters. The shape of the differential cross section is mainly determined by the underlying QCD cross sections and the parton density functions. With m_c fixed at 1.5 GeV/c^2 we performed fits with several

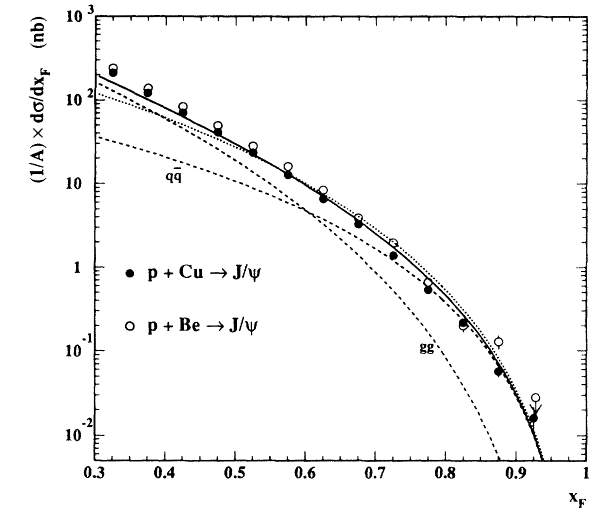

FIG. 2. Differential cross sections for J/ψ produced by protons. Solid points are $p + {\rm Cu} \to J/\psi$, and hollow points are $p + {\rm Be} \to J/\psi$. The solid curve is the fit of the semilocal duality model to the copper data using the DO set 1.1 parton density functions, with dashed curves showing the contributions of the gluon fusion and quark annihilation processes to the differential cross section. The dotted line shows the worst fit to the copper data, using the leading order GRV parton distributions.

current sets of leading order parton density functions: The Duke-Owens (DO) set 1.1 [14], the Morfin-Tung (MT) set [15], and the Gluck-Reya-Vogt (GRV) set [16], as given in PDFLIB [17]. Of these, both the DO and MT sets describe our data qualitatively ($\chi^2/N_{\rm DF} \approx 20$ for the Cu data). The prediction of the DO set 1.1 is compared with the data in Fig. 2. For the Be data the fits are somewhat better ($\chi^2/N_{\rm DF} \approx 6$). As shown for comparison in Fig. 2, the GRV set still qualitatively describes the data. If m_c is allowed to vary from 1.3 to 1.7 GeV/c^2, for the DO set 1.1, the differential change in the shape of the cross section between $x_F = 0.3$ and 0.9 varies within $\pm 10\%$ of that for $m_c = 1.5$ GeV/c^2. Note that we have neglected nuclear effects such as parton shadowing and the A dependence of the parton functions. These variations complicate any quantitative comparison of predictions with our results.

A third component was also added to the fit to search for an intrinsic charm (IC) contribution to the cross section, predicted to be 1.8 nb/nucleon in Cu and 3.2 nb/nucleon in Be [2,18]. At the 95% confidence level we obtained an upper limit for the IC contribution of $< 2.3 \times 10^{-3}$ nb/nucleon for Cu ($< 1.3 \times 10^{-2}$ nb/nucleon for Be); these limits are insensitive to the choice of m_c, and parton density functions.

A common parametrization for the A dependence of the production cross section is

$$\frac{d\sigma_A}{dx_F} = \frac{d\sigma_0}{dx_F} A^\alpha , \tag{2}$$

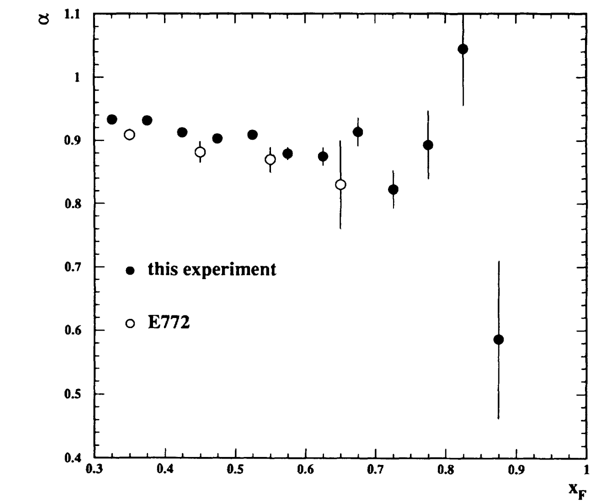

FIG. 3. The exponent α of the A dependence of J/ψ production. The solid points are from this experiment. The open circles are from Ref. [2]. Only statistical errors are shown.

where $d\sigma_0/dx_F$ is the p-nucleon cross section, and α, dependent on x_F and $p_\perp$, characterizes the nuclear dependence. In the limit of pure hard scattering with no nuclear effects $\alpha=1$, while in the diffractive limit, $\alpha=2/3$, $d\sigma_A/dx_F$ scales with the nuclear surface area. A value $\alpha<1$ characterizes a suppression in heavy nuclei.

Figure 3 shows the measured α as a function of x_F. Only statistical errors are shown. The overall systematic uncertainty in α is ± 0.025. The measurements of Alde *et al.* [3] are also shown for comparison. Within the systematic uncertainties of the measurements, the results are in fair agreement. Differences could be due to the different target materials and $p_\perp$ ranges covered in the two experiments.

In conclusion, we have measured the production of J/ψ over a wide range of x_F in 800 GeV/c p-Cu and p-Be reactions. With current sets of parton distributions (without any nuclear dependence corrections) the semilocal duality model can qualitatively describe the differential cross sections. Limits on a possible intrinsic charm component in the proton are given.

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$$(p_L^*)_{\max}=\sqrt{[s-(m_{\mu\mu}+2m_p)^2][s-(m_{\mu\mu}-2m_p)^2]}/2\sqrt{s}\ .$$

This accounts for the effect of nonzero final state masses, including the minimum mass of the recoil system.

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