Nuclear-Target Effects in J/ψ Production in 125-GeV/c Antiproton and π^- Interactions

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The production of the J/ψ resonance in 125-GeV/c $\bar{p}$ and ϕ^- interactions with Be, Cu, and W targets has been measured. The cross section per nucleon for J/ψ production is suppressed in W interactions relative to the lighter targets, especially at large values of Feynman x, which is opposite to the expectation from the various explanations of the European Muon Collaboration effect. Models incorporating modifications of the gluon structure functions in heavy targets show qualitative agreement with the data.

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Heavy-target effects observed in deep-inelastic scattering of electrons and muons from heavy nuclei[1,2] have been interpreted to be due to the distortions of the free-nucleon quark structure functions within the target nucleus. Observation of heavy-target effects in J/ψ production offers the opportunity to infer modifications of the gluon structure function in heavy targets in an analogous manner.[3] We have previously reported[4] the measurement of the production of high-mass muon pairs ($M > 4.0$ GeV/c^2) by 125-GeV/c π^-W and $\bar{p}$W interactions in a dimuon spectrometer[5] at the Fermi National Accelerator Laboratory in experiment E537. During this experiment, we also measured J/ψ production from 1-absorption-length beryllium, copper, and tungsten targets.

The measured cross sections are given in Table I. The data have been corrected for background under the J/ψ (8%), acceptances, detector and trigger efficiencies, and multiple interactions in the target [$(4.5 \pm 2.5)\%$].[6] Fermi motion of the target nucleons caused a change in the average center-of-mass energy of less than 0.5%. Smearing of the x_F and p_t variables due to Fermi motion was corrected by Monte Carlo simulation with a simple Fermi-gas model.[6] The number of ψ' into μ pairs was determined to be $(2.0 \pm 1.0)\%$ and $(2.6 \pm 0.7)\%$ of the number of J/ψ into μ pairs for the $\bar{p}$W and π^-W interactions, respectively, and was subtracted from the J/ψ signal.

Fitting the A dependence of the cross section to

$$\sigma_A = \sigma_N A^\alpha \tag{1}$$

for these three targets yields $\alpha(\pi^-) = 0.87 \pm 0.02$ and $\alpha(\bar{p}) = 0.90 \pm 0.03$. In both cases the heavier target is less efficient per nucleon in the production of J/ψ's. Figure 1 shows the result of the fit along with data from this experiment and the appropriately scaled[7] H_2 and Pt data from NA3.[8] Form (1) is clearly not adequate to describe the variation with atomic number. We have also fitted the A dependence of the π^- data for both experiments to the simple polynomial form $\sigma/A = (a + bA)$ and obtained $a = 63.17 \pm 2.0$ and $b = -0.110 \pm 0.01$ for $\chi^2/$d.o.f. $= 0.53$. This fit is also shown in Fig. 1 for the π^- data and scaled down by 0.834 for the $\bar{p}$ data.

We have studied the A dependence of the J/ψ cross sections as a function of Feynman x (x_F) and transverse

TABLE I. Total cross sections ($x_F > 0$) for J/ψ production from Be, Cu, and W at 125 GeV/c (nanobarns per nucleus). Errors are statistical and include background subtraction. The number of J/ψ's in each data sample is given in parentheses following the cross sections. Systematic errors are ±6% on all cross sections.

Target Beam	Be	Cu	W
π^-	560 ± 18 (2881)	3610 ± 112 (1958)	7900 ± 63 (33820)
$\bar{p}$	462 ± 18 (588)	2820 ± 110 (529)	6900 ± 89 (12530)

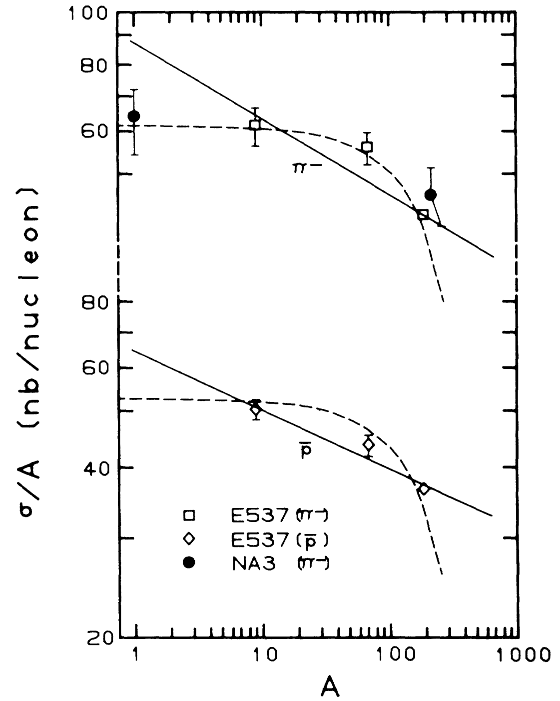

FIG. 1. Total J/ψ production cross section ($x_F > 0$) divided by the atomic weight (A) vs A for 125-GeV/c π^- and $\bar{p}$ interactions on Be, Cu, and W targets (statistical errors only). Also shown is the average of the NA3 150-, 200-, and 280-GeV/c $\pi^- H_2$ and π^-Pt J/ψ production cross sections (Ref. 8) extrapolated to 125 GeV/c. The solid lines are fits to the E537 data of the form $\sigma = \sigma_N A^\alpha$ with $\alpha = 0.87$ for π^- and $\alpha = 0.90$ for $\bar{p}$ data. The dotted lines are a polynomial fit to the π^- data (see text), also shown scaled by 0.834 for the $\bar{p}$ data.

momentum (p_t) by forming the ratios

$$R_1(\text{beam}, A_1/A_2) = \frac{(1/A_1) d\sigma/dx_F|_{A_1}}{(1/A_2) d\sigma/dx_F|_{A_2}},$$
$$R_2(\text{beam}, A_1/A_2) = \frac{(1/A_1) d\sigma/dp_t|_{A_1}}{(1/A_2) d\sigma/dp_t|_{A_2}}, \qquad (2)$$

in which systematic effects approximately cancel. As shown in Fig. 2(a), $R_1(\pi^-, \text{W/Be})$ shows a decrease at high x_F (or low x_2, $x_2 = \frac{1}{2}\{-x_F(1-\tau) + [x_F^2(1-\tau)^2 + 4\tau]^{1/2}\}$) and the same trend is seen in the $\bar{p}$ data. Similar trends have been seen in the measurements of J/ψ production in π^- and p interactions with nuclear targets by other experiments.[8,9] The ratios $R_2(\pi^-, \text{W/Be})$ and $R_2(\bar{p}, \text{W/Be})$ shown in Fig. 2(b) indicate suppression at low p_t. When $R_1(\pi^-, \text{W/Be})$ is determined for low- ($p_t < 1.2$ GeV/c) and high- ($1.2 < p_t < 3.0$ GeV/c) p_t regions, the value is the smallest in the low-p_t region [Fig. 3(a)]. When $R_2(\pi^-, \text{W/Be})$ is calculated for two different x_F regions ($0.0 < x_F < 0.3$ and $0.3 < x_F < 1.0$) both the absolute value and the shape of the distribution are observed not to depend on the x_F region [Fig. 3(b)]. Therefore, the decreased effectiveness per nucleon of the heavy target in the production of J/ψ seems to be preferentially present in the low-p_t region.

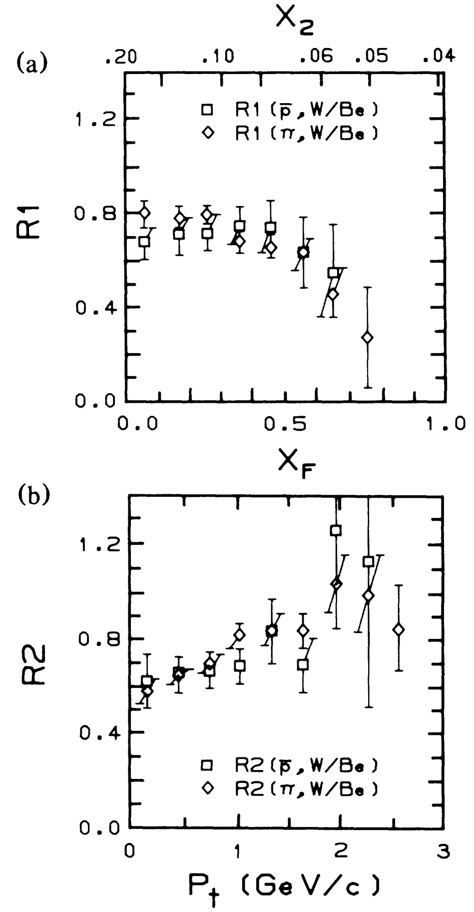

FIG. 2. (a) The ratio of ($A^{-1} d\sigma/dx_F$) for J/ψ production in π^-W and $\bar{p}$W to π^-Be and $\bar{p}$Be interactions at 125 GeV/c, as a function of x_F. (b) The ratio of ($A^{-1} d\sigma/dp_t$) for J/ψ production in π^-W and $\bar{p}$W to π^-Be and $\bar{p}$Be interactions at 125 GeV/c, as a function of p_t.

In order to investigate the dependence of R_1 on the nucleus, the ratios $R_1(\pi^-, \text{W/Cu})$ and $R_1(\pi^-, \text{W/Be})$ are shown in Fig. 4. While the statistical significance of the differences is limited, $R_1(\pi^-, \text{W/Be})$ is systematically lower than $R_1(\pi^-, \text{W/Cu})$ (in agreement with the total J/ψ production cross section) but shows the same variation with x_F. Similar nuclear effects have been observed in other reactions. Charmed-meson production per nucleon in π^- and proton interactions is also suppressed for heavy targets.[10] Suppression at high x_F is also observed in the production of kaons and other light particles from heavy nuclei.[11]

Several mechanisms have been proposed to soften the quark momentum (x_2) distribution in heavy nuclei in order to explain the observation of nuclear effects in deep-inelastic lepton scattering: rescaling of nuclear confinement sizes,[12] an increased soft-pion cloud,[13] and six-quark clustering.[14] In comparing these European Muon

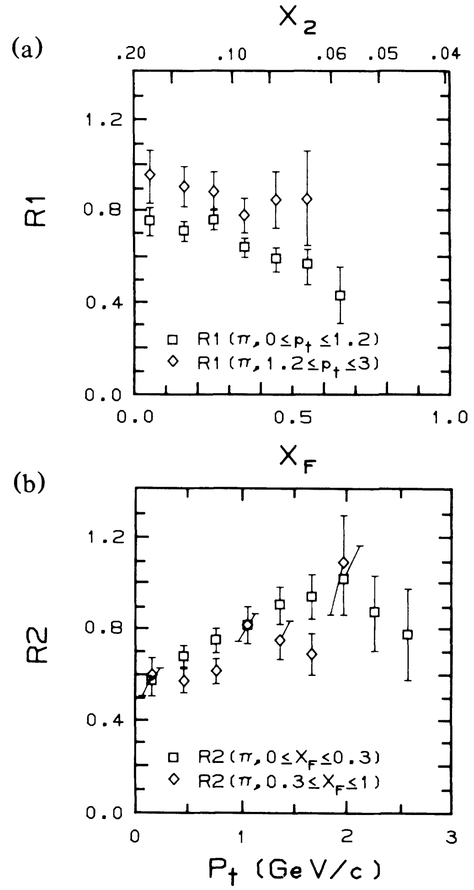

FIG. 3. (a) The ratio of $(A^{-1}d\sigma/dx_F)$ for π^-W to π^-Be for the $p_t < 1.2$ GeV/c and $1.2 < p_t < 3.0$ GeV/c regions, as a function of x_F. (b) The ratio of $(A^{-1}d\sigma/dp_t)$ for π^-W to π^-Be for the $0 < x_F < 0.3$ and $0.3 < x_F < 1.0$ regions, as a function of p_t.

Collaboration effect models to our $\pi^- N \rightarrow J/\psi$ data, we have assumed that J/ψ production proceeds via gg and $q\bar{q}$ fusion in the semilocal-duality model.[15] For the nucleons, we have used the free-quark structure functions of Duke and Owens (set 1)[16] and a gluon structure function derived from our own $\bar{p}\mathrm{W} \rightarrow J/\psi$ data.[17] We have assumed that the gluon structure function has no nuclear dependence. The π^- gluon and quark structure functions were derived from our $\pi^-\mathrm{W} \rightarrow J/\psi$ data.[17] These models are compared in Fig. 5 with the ratio R_1. If these effects are present, they are masked by a much stronger effect since the yield of J/ψ from heavy targets decreases at high x_F while an increase is predicted.

We have examined three other proposed mechanisms that better describe the features of our data: a suppression per nucleon in the production of J/ψ's with $x_F > 0$ in heavy targets that increases with increasing x_F and decreases with increasing p_t. A significant portion of the J/ψ production may proceed via three-gluon fusion.[18] This mechanism produces a harder effective gluon momentum (x_2) distribution in heavy targets, causing a decrease in J/ψ production for $x_F > 0$ and in particular at high x_F. The collinearity requirement for three-gluon fusion suggests that the effect disappears at high p_t. In the nuclear shadowing model,[19] the soft parton component of a nucleon in a nucleus is depleted by the migration and recombination of partons between nucleons resulting in modifications of the x_F distribution similar to the gluon-fusion model. The rescattering model[20] is the scattering by a neighboring nucleon of the beam before the production of the J/ψ takes place, or scattering of the J/ψ itself after production. The process significantly decreases the number of J/ψ with $x_F > 0$, particularly at high x_F. The effect decreases with increasing p_t due to the broadening of the p_t distribution in heavy targets. Scattering of the J/ψ appears to be the most likely of the "rescatterings" since initial-state scattering is not observed in Drell-Yan production.[21]

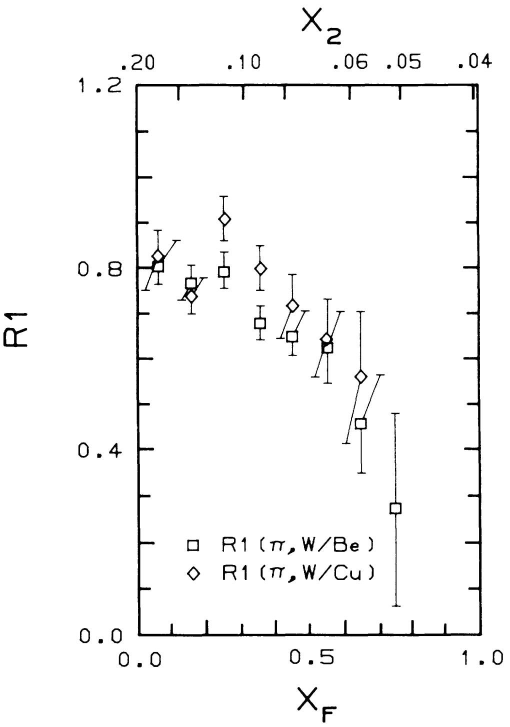

FIG. 4. The ratios of $(A^{-1}d\sigma/dx_F)$ for π^-W to π^-Be and $(A^{-1}d\sigma/dx_F)$ for π^-W to π^-Cu as a function of x_F.

Calculations of these three mechanisms (with the semilocal-duality model of Ref. 15 used for the basic J/ψ production mechanism for the rescattering and shadowing calculations, and with the modified structure functions from the shadowing model[19]) are also shown in Fig. 5. They all predict an overall decrease in the production of J/ψ per nucleon in W relative to Be and a decrease in R_1 at high x_F.

In conclusion, we have observed heavy-target effects in the production of the J/ψ resonance. There is a suppression of J/ψ production per nucleon in both π^-W and $\bar{p}$W interactions relative to π^-Be and $\bar{p}$Be interactions.

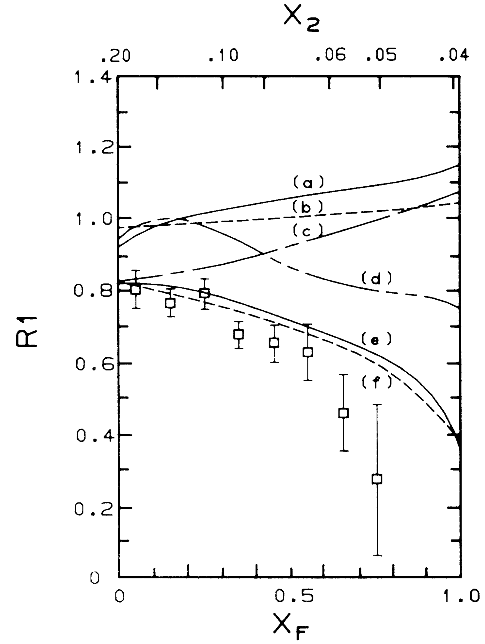

FIG. 5. Comparison of the ratio $(A^{-1}d\sigma/dx_{\rm F})$ for π^-W to π^-Be to various models: curve *a*, soft-π model; curve *b*, rescaling model; curve *c*, six-quark model; curve *d*, shadowing model; curve *e*, rescattering model; and curve *f*, three-gluon-fusion model without $q\bar{q}$ contributions.

For π^- production the A dependence of the total cross section does not follow the form A^α. The suppression for heavy targets becomes more pronounced at high $x_{\rm F}$. Similar trends are observed for $\bar{p}$ production of J/ψ's. In addition, the production of J/ψ's by π^-'s and $\bar{p}$'s at low p_t is suppressed in W relative to Be, with the effect diminishing towards higher p_t. These observations cannot be explained by the various mechanisms proposed to describe nuclear effects in deep-inelastic lepton scattering. We can find qualitative explanation using models of J/ψ production which harden the gluon distribution of the target nucleon, absorb the soft parton component in the target nucleon, or allow rescattering of the J/ψ.

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