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EXPERIMENTAL RESULTS ON J/ψ PRODUCTION BY $\pi^\pm$, $K^\pm$,
 p AND $\bar{p}$ INCIDENT ON HYDROGEN AT 39.5 GeV/c

M.J. Corden, J.D. Dowell, J. Garvey, R.J. Homer, M. Jobes
I.R. Kenyon, T. McMahon, R.C. Owen, K.C.T.O. Sumorok,
R.J. Vallance, P.M. Watkins and J.A. Wilson

Birmingham University, Birmingham, U.K.

P. Sonderegger

CERN, Geneva, Switzerland

B. Chaurand, A. Romana and R. Salmeron

Ecole Polytechnique, Palaiseau, France

ABSTRACT

J/ψ production at 40 GeV/c by $\pi^\pm$, $K^\pm$, p and $\bar{p}$ incident on hydrogen has been studied and results compared with those obtained on tungsten in the same experiment. On hydrogen, J/ψ cross-section ratios relative to π^- have been measured to be (for $x_F > 0$):

$$\sigma(\pi^-):\sigma(\pi^+):\sigma(\bar{p}):\sigma(p) = 1:(0.78\pm0.09):(0.83\pm0.35):(0.07\pm0.04)$$

The suppression of the proton induced cross-sections shows the importance of valence quark-antiquark fusion in J/ψ production at this energy (i.e., $M_{J/\psi}^2/s = 0.13$).

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The production of J/ψ , decaying into $\mu^+\mu^-$, was measured at 39.5 GeV/c using both negative and positive unseparated beams from the CERN SPS incident on hydrogen and tungsten targets, located in the Omega Spectrometer (1). Results on J/ψ production on hydrogen are presented here. Corresponding results on tungsten have been discussed in an earlier paper (2).

Relatively few results exist for J/ψ production on liquid hydrogen targets. Bamberger et al (3) have reported on J/ψ production by 24 GeV/c protons in a bispectrometer experiment and Kirk et al (4) have measured the production of dimuons and associated photons on hydrogen and beryllium targets using a 215 GeV/c π^- beam. Results on J/ψ production on hydrogen and tungsten by $\pi^\pm$, $K^\pm$, $\bar{p}$ and p at 150 GeV/c and 200 GeV/c are presented by Badier et al (5) and these data complement the lower energy measurements reported here.

The apparatus and trigger logic used in this experiment are described elsewhere (2). Data taking on hydrogen and tungsten targets proceeded simultaneously, with the same trigger conditions which removed most relative normalization uncertainties. The dimuon acceptance of the apparatus was calculated assuming an isotropic decay of the J/ψ in its rest frame. In this paper, data are presented for $x_F > 0$ where dimuon acceptance is greater than 5% for all p_t and has an average value of 20%.

Apart from the selection of dimuons originating in the hydrogen target, the normalization and analysis procedure, described in ref. 2, was used. An estimate of the vertex location along the beam direction was obtained by extrapolating the muon tracks, reconstructed in the optical spark chambers, to intersect the beam axis in the horizontal and vertical planes. In order to eliminate events from the tungsten target, the averaged intersection point, X_0 , of the muon tracks with the incident beam was required to lie within 15cm of the hydrogen target. This cut removed approximately 5% of the events in the J/ψ region ($2.7 < m_{\mu\mu} < 3.5 \text{ GeV}/c^2$), in agreement with Monte Carlo calculations.

Data surviving these cuts were analysed further using the information from seven planes of multiwire proportional chambers, placed between the hydrogen and tungsten targets. In 88% of the events, it was possible to use the vertical projections of the tracks in these chambers to calculate a vertex position, X_m . The vertex reconstruction efficiency did not depend on the dimuon mass. Events were rejected when the difference in estimated vertices, $|X_m - X_0|$, exceeded 28cm. This cut involved a negligible loss of J/ψ events. A recalculation of the dimuon mass, using the muon angles corrected at the vertex determined by the wire chambers, gave a factor 2 reduction in J/ψ width compared to the mass calculated at the hydrogen target centre.

In the J/ψ mass region, 402 dimuons were produced by negative beam while the corresponding number for positive beam was 191. Effective mass distributions, corrected for experimental acceptance, are shown in figures 1(a-d) for π^- , π^+ , $\bar{p}$ and p induced dimuons with mass greater than $1.7 \text{ GeV}/c^2$ and $x_F > 0$. For π^+ and π^- , clear J/ψ signals, as well as shoulders on the high mass side which we interpret as ψ' production, are observed. The fitted curves on figures 1a and 1b are Gaussian shapes for the J/ψ and ψ' superimposed on an exponential background. For π^- induced events, the fitted J/ψ mass and width are $(3.10 \pm 0.01) \text{ GeV}/c^2$ and $(0.29 \pm 0.01) \text{ GeV}/c^2$ while for the π^+ induced events, the corresponding values are $(3.12 \pm 0.01) \text{ GeV}/c^2$ and $(0.33 \pm 0.02) \text{ GeV}/c^2$. For both π^+ and π^- , the ψ' mass and width were fixed at $3.68 \text{ GeV}/c^2$ and $0.32 \text{ GeV}/c^2$ respectively. Among the minority beam particle types a clear J/ψ signal is seen only for $\bar{p}$.

In the case of π^+ and π^- , the fitted numbers of J/ψ events are used in the cross section calculation. For the minority beam particle types, one estimate of the J/ψ signal is made by subtracting the events in adjacent sidebands from those in the J/ψ region. This assumption of a linear background underestimates the J/ψ signal. An overestimate is provided by taking the numbers of events in the J/ψ region

itself. The average of the two estimates is used to calculate the cross section. Cross sections were obtained using the incident beam fluxes measured as in ref(2) and allowing for the different absorption length of each beam particle type in hydrogen. In the J/ψ region, the empty target rate is less than 3% while the contamination from K and π decays, measured by like-sign muon pairs, is less than 5%. These contributions were not subtracted in the cross section calculation. The J/ψ cross sections and cross section ratios, relative to the π^- induced, are shown in Table 1. Cross section errors in Table 1 are statistical only but cross section ratios for beam particles of opposite sign are assigned an additional error of $\pm 4\%$ due to relative beam normalization uncertainties. An overall systematic error of $\pm 15\%$ to cover uncertainties in the beam flux measurement and acceptance calculation has not been included in Table 1; neither has the uncertainty in the $J/\psi \rightarrow \mu^+\mu^-$ branching ratio. The π^- induced J/ψ cross section on protons for $x_F > 0$, was measured to be $(14.5 \pm 0.9) \text{ nb}$. For the minority beam particle types, the cross section errors are large but J/ψ production by protons is significantly less than that by antiprotons and π^- .

Our previous measurements of J/ψ production on copper⁽⁶⁾ and tungsten⁽²⁾ at 40 GeV/c yielded small $p/\bar{p}$ and K^+/K^- cross section ratios while the π^+/π^- cross section ratio was found to be approximately unity. These results showed clearly the importance at this energy (where $M_{J/\psi}^2/s=0.13$) of valence quark-antiquark fusion in J/ψ production where the absence of valence antiquarks in the proton and K^+ leads to a suppressed cross section. For an isoscalar target, the π^+/π^- cross section ratio is expected to be unity. In the case of hydrogen, however, the π^+/π^- cross section ratio is expected to be less than unity if valence quark-antiquark fusion is an important mechanism. Our measured cross section ratios on hydrogen, $\sigma(\pi^+)/\sigma(\pi^-)=0.78\pm0.09$, $\sigma(p)/\sigma(\pi^-)=0.07\pm0.04$ and $\sigma(p)/\sigma(\bar{p})=0.08^{+0.3}_{-0.06}$, reinforce the conclusion that valence quark-antiquark fusion is an important, but not the only, mechanism of J/ψ production at 40 GeV/c. At 150 GeV/c, Badier et al⁽⁵⁾ have measured cross section ratios on hydrogen to be $\sigma(\pi^+)/\sigma(\pi^-) = 0.94\pm0.08$ and $\sigma(p)/\sigma(\bar{p})= 0.51\pm0.09$ while, at 200 GeV/c, they measured $\sigma(\pi^+)/\sigma(\pi^-)=0.99\pm0.06$. The trend of these ratios towards unity as energy increases illustrates the diminishing importance of valence quark-antiquark fusion as $M_{J/\psi}^2/s$ decreases.

The production cross sections for ψ' are also shown in Table 1. The ψ'/ψ cross section ratios for $x_F>0$ were

measured to be (0.4 ± 0.2) and (0.9 ± 0.4) for π^+ and π^- respectively. Corresponding ratios for tungsten ⁽²⁾ were (0.27 ± 0.09) and (0.32 ± 0.11) , which are consistent within the errors of the hydrogen measurements. Thus, approximately one-third of the observed J/ψ production in hydrogen must be attributed to ψ' decays.

The acceptance corrected x_F distributions in the J/ψ region are shown in figures 2a and 2b for incident π^+ and π^- (for $x_F > 0$). Similarly shaped distributions, peaking at a positive value of x_F , were observed for J/ψ production on tungsten.

The p_t^2 distributions, corrected for acceptance, in the J/ψ region and with $x_F > 0$ are shown in Figure 3 for incident π^+ and π^- . For $p_t^2 < 4.0$ $(\text{GeV}/c)^2$, the distributions are fitted well by the form $\frac{d\sigma}{dp_t^2} \propto \exp(-bp_t^2)$ where b equals (1.19 ± 0.12) $(\text{GeV}/c)^{-2}$ and (1.46 ± 0.08) $(\text{GeV}/c)^{-2}$ for π^+ and π^- respectively. Average values of p_t^2 are measured to be (0.86 ± 0.08) $(\text{GeV}/c)^2$ and (0.76 ± 0.06) $(\text{GeV}/c)^2$ for π^+ and π^- respectively, where allowance has been made for the smearing effect of multiple scattering. Corresponding values for J/ψ produced on tungsten ⁽²⁾ (and for $x_F > 0$) are (0.82 ± 0.02) $(\text{GeV}/c)^2$ and (0.80 ± 0.01) $(\text{GeV}/c)^2$. The similarity in results between free nucleon and heavy nuclear targets suggests that there is a negligible

contribution to the dimuon average transverse momentum arising from nuclear effects.

The variation of cross section, σ , with target atomic weight, A , is usually parameterized as $\sigma = \sigma_0 A^\alpha$. We define a quantity R which is equal to $A^{1-\alpha}$. Averaging between π^+ and π^- to eliminate any effect due to the inequality of numbers of u and d quarks in the target nucleus, R can be expressed as $A^{1-\alpha} = A (\sigma(\pi^+) + \sigma(\pi^-))_{H_2} / (\sigma(\pi^+) + \sigma(\pi^-))_W$. By comparing the measured J/ψ cross sections for $x_F > 0$ on hydrogen (this experiment) and on tungsten (2), R was measured to be (1.13 ± 0.12) yielding a value of α of (0.98 ± 0.02) . This result is slightly higher than previous measurements (5,7,8). J/ψ cross sections measured in other experiments (6,8,9) on copper at nearly 40 GeV/c were compared with cross sections obtained by interpolating our tungsten results to copper using our measured A dependence. Reasonable agreement was obtained within our quoted $\pm 15\%$ overall systematic error. The x_F and p_t dependence of α was determined from the behaviour of the ratio, R , as a function of x_F and p_t . The measured α falls by 10% between $x_F = 0$ and $x_F = 0.8$ and rises by 10% between $p_t^2 = 0$ and $p_t^2 = 4$ (GeV/c)². However, both effects lie within our experimental uncertainties.

To conclude, the above results on hydrogen provide further information on the J/ψ production mechanism. In

particular, the J/ψ cross section ratios, (for $x_F > 0$),
 $\sigma(\pi^+)/\sigma(\pi^-) = 0.78 \pm 0.09$, $\sigma(\bar{p})/\sigma(\pi^-) = 0.83 \pm 0.35$ and $\sigma(p)/\sigma(\pi^-)$
 $= 0.07 \pm 0.04$, confirm the importance of the valence
quark fusion mechanism at 40 GeV/c. Significant ψ' production
has been observed in agreement with our results on J/ψ
production on tungsten. The x_F and p_t^2 distributions of the
 J/ψ show no qualitative difference from the tungsten data.
The J/ψ cross section for $x_F > 0$ was parameterized as $\sigma \sim A^\alpha$ and α
was measured to be 0.98 ± 0.02 .

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Table 1 (as explained in text)

	$x_F > 0$					
	π^-	π^+	K^-	K^+	$\bar{p}$	p
Total J/ψ cross section (nb/nucleon) [using $BR(J/\psi \rightarrow \mu^+\mu^-) = 0.07$].	14.5 ± 0.9	11.3 ± 1.0	4.4 ± 3.0	7.5 ± 4.0	12.0 ± 5.0	1.0 ± 0.5
J/ψ cross section relative to π^-	1	0.78 ± 0.09	0.30 ± 0.21	0.52 ± 0.28	0.83 ± 0.35	0.07 ± 0.04
Total ψ' cross section (nb/nucleon) [using $BR(\psi' \rightarrow \mu^+\mu^-) = 0.008$]	13.5 ± 6.0	4.8 ± 3.0	-	-	-	-

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Figure Captions

Fig 1(a,b,c,d) Number of dimuons, corrected for experimental acceptance, produced for $x_F > 0$ by π^- , π^+ , $\bar{p}$ and p beam particles incident on a hydrogen target. (N.B. The acceptance weight for each event is calculated assuming the dimuon has the J/ψ mass).

Fig 2(a,b) Branching ratio, $BR(J/\psi \rightarrow \mu\mu)$, times $\frac{d\sigma}{dx_F}$ for π^+ and π^- induced dimuons in the J/ψ region, $2.7 < m < 3.5 \text{ GeV}/c^2$.

Fig 3 Branching Ratio, $BR(J/\psi \rightarrow \mu\mu)$, times $\frac{d\sigma}{dp_t^2}$ for π^+ and π^- induced dimuons in the J/ψ region and with $x_F > 0$. The straight lines drawn through the data points are the exponential fits described in the text.

Fig. 1

Fig. 2

Fig. 3