EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/80-140
7 July 1980

EXPERIMENTAL RESULTS ON J/ψ PRODUCTION BY π^+ , K^+ , p and $\bar{p}$

BEAMS AT 39.5 GeV

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(Submitted to Physics Letters)

Abstract

The production of J/ψ by $\pi^\pm$, $K^\pm$, p and $\bar{p}$ incident on tungsten at 39.5 GeV/c beam momentum has been studied. Production of $\psi'(3700)$ by $\pi^\pm$ was also observed. The J/ψ relative particle/antiparticle cross-sections for $x_F > 0$ are $\sigma(\pi^+)/\sigma(\pi^-) = (1.01 \pm 0.06)$, $\sigma(K^+)/\sigma(K^-) = (0.29 \pm 0.07)$ and $\sigma(p)/\sigma(\bar{p}) = (0.19 \pm 0.03)$. The small $p/\bar{p}$ and K^+/K^- cross-section ratios indicate the importance of valence quarks in the production process.

The production of the J/ψ decaying into $\mu^+\mu^-$ has been measured at 39.5 GeV/c using $\pi^\pm$, $K^\pm$, p and $\bar{p}$ in unseparated beams at the CERN SPS incident on hydrogen and tungsten targets located in the Omega spectrometer¹⁾. This has yielded a tenfold increase over our previous experiment at this beam energy²⁾ which was the first to measure cross-section ratios for J/ψ production between all types of beam particle. In this letter we report the results for tungsten which cover effectively the full range of x_F .

The apparatus is shown schematically in Fig. 1. Three threshold Cerenkov counters and a CEDAR³⁾ differential Cerenkov counter identified the beam particles. Perspex Cerenkov counters C3, C4 and scintillation counters, S1 and S3, defined the incident beam with veto counters V2 and V3 providing protection against beam tails and halo muons. Crossed scintillation hodoscopes H1 and H2, each consisting of twelve narrow scintillators with widths chosen to match the beam profile, were used to provide positional and timing information on the beam particles, and to count the incident beam flux.

At Omega the beam particles were incident on a 67 cm liquid hydrogen target followed by seven closely spaced multiwire proportional chamber planes and then a 6 cm tungsten target, the distance between target centres being 93 cm. The tungsten target was separated by an air space of 30 cm from a 1.1 m thick copper absorber containing a central plug of tungsten of half angle 50 mrad with a front face of area $4 \times 2 \text{ cm}^2$. Particles emerging from the absorber were detected with a segmented scintillation counter hodoscope, S6, comprising seventeen horizontal slabs each with dimensions $150 \times 6.3 \times 2 \text{ cm}^3$. Photomultipliers at each end of each slab were used to generate a 4 ns coincidence for the muon trigger. VO was used to veto beam muons. Particle trajectories were recorded with a TV readout of forty optical spark chamber gaps, in a region of 1.7 T magnetic induction. A multiwire proportional chamber was placed behind the spark chambers. Particles leaving the chamber system passed into the 1.25 m thick iron return yoke of the magnet which acted as a second hadron absorber before a final counter hodoscope (BH) of sixty elements arranged as three vertical columns each containing twenty horizontal slabs covering an area 6 m wide and 4 m high. Pulse height and timing information were recorded on tape for all of the

scintillators and Cerenkov counters used in the experiment.

Correlations between hits in S6 and BH were imposed electronically corresponding to tracks originating from the hydrogen or tungsten targets within the limits imposed by multiple scattering. At least one track candidate above and one below the median plane were required, accompanied by a beam hadron, to trigger the spark chambers.

The data presented in this paper correspond to approximately 1,258,000 triggers with negative beam and 867,000 triggers with positive beam. The beam intensity was typically 10^7 per burst in an effective spill of 700 ms and the trigger rate 15 per burst. The beam Cerenkov counters were equipped with fast RCA C31024 photomultipliers giving 5 ns pulses. Usually the CEDAR counter was set to record kaons while the pions and protons (antiprotons) were detected using the threshold Cerenkov counters but as a cross check the CEDAR was set to count protons (antiprotons) for about 20% of our data. Less than 0.2% (0.8%) of the proton (antiproton) sample were found to be misidentified pions. Beam fractions were measured to be $(93.9 \pm 1.0)\% \pi^-$, $(3.4 \pm 0.3)\% K^-$, $(2.7 \pm 0.3)\% \bar{p}$ and $(74.6 \pm 1.0)\% \pi^+$, $(3.4 \pm 0.3)\% K^+$ and $(22.0 \pm 1.0)\% p$.

All triggers were processed through a modified version of the offline pattern recognition and geometrical reconstruction program ROMEO⁴⁾. Tracks were classified as muons if they corresponded to hits in the hodoscopes S6 and BH within the multiple scattering uncertainty. The average correlation between the angle and position displacements arising from multiple scattering was used to correct the angles of the tracks extrapolated to the target.

The negative and positive beam data yielded 11,506 and 5,677 events respectively containing a $\mu^+\mu^-$ pair with effective mass above $2 \text{ GeV}/c^2$ and satisfying the following criteria : a) the momentum of each muon was less than $30 \text{ GeV}/c$ and the sum of the two momenta did not exceed the beam momentum within measurement errors ; b) the average crossing point of the tracks with the beam in the horizontal and vertical track projections was within 12.5 cm of the centre of the tungsten target along the beam direction.

The acceptance of the apparatus was calculated using Monte Carlo events generated for unpolarised J/ψ production and a weight applied to each event. The average acceptance for $x_F > 0$ was 30% and fell to 1.5% at $x_F = -0.5$.

The weighted $\mu^+\mu^-$ mass spectra for masses greater than $1.5 \text{ GeV}/c^2$ are shown in Fig. 2(a-f). Clear J/ψ signals are seen in all cases. For π^+ and π^- shoulders on the high mass side of the J/ψ are observed which we interpret as ψ' production. The fitted curves on Fig. 2 are Gaussians superimposed on an exponential background. The fitted J/ψ masses for π^+ and π^- induced events are $3.104 \pm 0.002 \text{ GeV}/c^2$ and $3.087 \pm 0.002 \text{ GeV}/c^2$ both with FWHM of $0.366 \pm 0.006 \text{ GeV}/c^2$.

Table I gives the cross-sections for $x_F > -0.5$ (effectively the whole region) and $x_F > 0$, deduced from the fitted numbers of events. In the J/ψ region, the empty target rate is negligible, as well as the contamination from K and π decays as measured by like-sign muon pairs. The contribution from secondary interactions was calculated to be negligible in agreement with a comparison made by varying the target length. In the case of p and $\bar{p}$ symmetry is expected about $x_F = 0$ and the cross-sections for $x_F > 0$ have been obtained by halving the total cross-section. The cross-section ratios relative to π^- and the particle-antiparticle ratios given in Table I confirm our earlier results²⁾. Cross-section errors include statistical errors and errors in beam particle fractions. Cross-section ratios for beam particles of opposite sign are assigned an additional error of $\pm 4\%$ due to relative beam normalization uncertainties. The J/ψ cross-sections for $\pi^\pm$, K^- and $\bar{p}$ are all similar within errors but the cross-sections for K^+ and p are lower by factors of 3.5 and 5 respectively. The particle/antiparticle ratios for $x_F > 0$ are $\pi^+/\pi^- = 1.01 \pm .06$, $K^+/K^- = 0.29 \pm 0.07$ and $p/\bar{p} = 0.19 \pm 0.03$. The π^- induced total J/ψ cross-sections was measured to be $2960 \pm 440 \text{ nb/W nucleus}$ for $x_F > -0.5$ and $2080 \pm 310 \text{ nb/W nucleus}$ for $x_F > 0$, the latter corresponds to $11.3 \pm 1.7 \text{ nb per nucleon}$ assuming a linear A-dependence and includes a systematic error of $\pm 15\%$ to allow for uncertainties in the beam flux and acceptance. In our previous experiment²⁾, this cross-section was found to be $14.3 \pm 2 \text{ nb/nucleon}$ on copper. The agreement is reasonable within our estimated overall systematic error.

A variety of methods have been used to estimate the amount of ψ' production. For example fits to the π^- and π^+ mass distributions in which the masses of the J/ψ and ψ' were allowed to vary, the widths were held equal but allowed to vary and the background was exponential

gave for the mass of the J/ψ $3.097 \pm 0.003 \text{ GeV}/c^2$ and $3.098 \pm 0.004 \text{ GeV}/c^2$ respectively and for the ψ' $3.687 \pm 0.029 \text{ GeV}/c^2$ and $3.680 \pm 0.027 \text{ GeV}/c^2$ with a common width of $0.440 \text{ GeV}/c^2$. The results given here were obtained by fixing the ψ' mass at $3.70 \text{ GeV}/c^2$ and the width at $0.42 \text{ GeV}/c^2$ and are consistent with those found by other methods. Corrections have been made to allow for the small difference in acceptance of the J/ψ and ψ' (3700). For incident π^- , the relative cross-section times branching ratio for ψ' and ψ was observed to be $(3.1 \pm 0.6)\%$ for $x_F > 0$ and $(4.6 \pm 1.0)\%$ for $x_F < -0.5$. Thus some 20% of the observed J/ψ production in our experiment must be attributed to the cascade $\psi' (3700) \rightarrow J/\psi \rightarrow \mu^+\mu^-$. The relative ψ' cross-section is larger than previously observed in experiments at $150 \text{ GeV}/c^5$ and $225 \text{ GeV}/c^6$. A study of the effect of systematic variations of the form of background under the ψ and ψ' and of the ψ' parameters showed the uncertainty in the production cross-section to be less than 20%.

The p_T^2 distributions for events in the J/ψ region ($2.7 < M_{\mu\mu} < 3.5 \text{ GeV}/c^2$) are well fitted for $p_T^2 < 2.0 (\text{GeV}/c)^2$ by the form $dN/dp_T^2 \propto \exp(-bp_T^2)$, but for higher values of p_T^2 the distributions become flatter. Values of b of 1.29 ± 0.03 and 1.34 ± 0.04 were obtained for π^- and π^+ respectively. Average values of p_T and p_T^2 are given in Table II and the $\langle p_T \rangle$ and $\langle p_T^2 \rangle$ for the rare particles are compatible with these within errors. Corrections have been applied to allow for the smearing effect of multiple scattering. For comparison the values of $\langle p_T^2 \rangle$ for π^- induced J/ψ found in other experiments are as follows : 40 GeV^2 , $0.77 \pm 0.07 (\text{GeV}/c)^2$; 200 GeV^7 , $1.70 \pm 0.03 (\text{GeV}/c)^2$; 225 GeV^6 , $1.47 \pm 0.10 (\text{GeV}/c)^2$; 280 GeV^7 , $1.86 \pm 0.02 (\text{GeV}/c)^2$. Our value of $0.90 \pm 0.03 (\text{GeV}/c)^2$ provides a clear indication of a rise of $\langle p_T^2 \rangle$ with increasing s . For both π^+ and π^- data $\langle p_T \rangle$ decreases as x_F increases.

The acceptance corrected x_F distributions for events in the J/ψ region ($2.7 < M < 3.5 \text{ GeV}/c^2$) are shown in Fig. 3 for incident π^+ and π^- . The distributions are approximately symmetric about $x_F = 0.14$ and are somewhat wider than those obtained at higher energies^{5,6,7}). In Figs. 4(a-b) the ratios K^-/π^- and K^+/π^+ are shown as a function of x_F . The nearly constant ratios indicate the distributions for the four mesons have similar shapes. Similar results have been obtained at $200 \text{ GeV}/c$ by Badier et al.⁷). In Figs. 4(c-d) the ratios $\bar{p}/\pi^-$ and p/π^+

are given. Both $\bar{p}$ and p show a steeper fall off with increasing positive x_F than the mesons and are similar in shape to each other although different in magnitude.

We have examined the decay angular distributions for π^+ and π^- events using both the Gottfried-Jackson and the Collins-Soper⁸⁾ frames of reference. The acceptance in $\cos\theta$ has been calculated assuming a flat ϕ distribution, as indicated by the data, and allowing for the smearing effect of multiple scattering. The $\cos\theta$ distributions in the G-J and C-S systems for π^+ and π^- are consistent with being isotropic. The values of a α parameter determined by fitting $(1+\alpha\cos^2\theta)$ for $x_F>0$ are 0.11 ± 0.19 and 0.01 ± 0.21 in the G-J and C-S systems respectively for π^+ . Corresponding values for π^- are 0.16 ± 0.16 and -0.07 ± 0.18 . There is no evidence of any x_F or p_T dependence of the shape of the angular distribution.

In conclusion, our results on J/ψ production from tungsten for all six beam particles are consistent with our earlier measurements²⁾. The π^- induced cross-section is found to be 2960 ± 440 (2080 ± 310) nb/W nucleus for all x_F ($x_F>0$). In particular we find the J/ψ cross-section ratios, $p/\bar{p} = 0.19\pm0.03$, $K^+/K^- = 0.29\pm0.07$ and $\pi^+/\pi^- = 1.01\pm0.06$. The small $p/\bar{p}$ and K^+/K^- ratios are indications of the importance of valence quarks in J/ψ production at 40 GeV/c. The average values of p_T and p_T^2 are considerably lower than those found at 200-280 GeV/c and $\langle p_T \rangle$ decreases as x_F increases. The shapes of the four meson x_F distributions are similar while those for p and $\bar{p}$ decrease much faster at large x_F reflecting their different structure functions. The decay angular distribution of the J/ψ shows no evidence of anisotropy or any x_F or p_T dependence. For π^+ and π^- clear evidence of ψ' production is observed giving a ratio to J/ψ of $(4.6\pm1.0)\%$ for the product of the cross-section times branching ratio ($x_F>-0.5$).

We thank the SPS crew and the staff of the Omega spectrometer. We thank also Dornach Metallwerk AG of Dornach Switzerland for lending us the copper for the absorber and L. Bassi and his group for the construction of the tungsten-copper absorber.

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TABLE I (as explained in text)

(Branching ratios, $B(J/\psi \rightarrow \mu^+ \mu^-) = 0.07$ and $B(\psi' \rightarrow \mu^+ \mu^-) = 0.008$, were used ; an overall systematic normalization error of $\pm 15\%$ is not included)

	$x_F > -0.5$						$x_F > 0$					
	π^-	π^+	K^-	K^+	$\bar{p}$	p	π^-	π^+	K^-	K^+	$\bar{p}$	p
Total ψ' cross-section (nb/W nucleus)	1183 ± 250	1130 ± 300					562 ± 165	679 ± 230				
Total J/ψ cross-section (nb/W nucleus)	2958 ± 84	3115 ± 117	2601 ± 418	901 ± 167	3830 ± 550	728 ± 88	2080 ± 67	2103 ± 67	1819 ± 260	525 ± 110	1915 ± 275	364 ± 44
J/ψ cross-section relative to that for π^-	1	1.05 ± 0.06	0.88 ± 0.11	0.30 ± 0.06	1.29 ± 0.14	0.24 ± 0.03	1	1.01 ± 0.06	0.87 ± 0.12	0.25 ± 0.05	0.92 ± 0.12	0.17 ± 0.02
Particle/Antiparticle cross-section ratios for J/ψ	1.05 $\pm$ 0.06		0.35 $\pm$ 0.07		0.19 $\pm$ 0.03		1.01 $\pm$ 0.06		0.29 $\pm$ 0.07		0.19 $\pm$ 0.03	

TABLE II

	$\langle p_T^2 \rangle$ (GeV/c ²)	$\langle p_T \rangle$ (GeV/c)	$\langle p_T \rangle$ (GeV/c)				
	$x_F > -0.5$	$x_F > -0.5$	$x_F < 0$	$0 < x_F < .25$	$.25 < x_F < .5$	$.5 < x_F < .75$	$x_F > .75$
π^-	$0.90 \pm .03$	$0.83 \pm .02$	$0.90 \pm .02$	$0.82 \pm .02$	$0.79 \pm .02$	$0.73 \pm .02$	$0.53 \pm .04$
π^+	$0.91 \pm .04$	$0.82 \pm .02$	$0.88 \pm .03$	$0.85 \pm .02$	$0.78 \pm .02$	$0.68 \pm .03$	$0.50 \pm .06$

Figure captions

1. Schematic diagram of apparatus.

2. (a-f) Mass distributions corrected for experimental acceptance for dimuons induced by each beam particle type on a tungsten target. The fitted curves are discussed in the text.
(Note that the acceptance weight for each event is calculated assuming the dimuon has the J/ψ mass. Therefore, the mass bins outside the J/ψ region cannot be used for cross-section calculations.)

3. Acceptance corrected x_F distribution for dimuons in the J/ψ region (background not subtracted) induced by a) π^+ and b) π^- .

4. Dimuon cross-section ratios on tungsten in the J/ψ region for a) K^-/π^- , b) K^+/π^+ , c) $\bar{p}/\pi^-$, d) p/π^+ , as a function of x_F .

Fig.1

Fig.2 (a-f)

Fig. 3

Fig. 4