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J/ψ PRODUCTION BY 24 GeV/c PROTONS

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ABSTRACT

We report measurements at the CERN PS of the production cross-section of J/ψ(3.1) by 24 GeV protons on hydrogen, carbon, and tungsten.

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1. INTRODUCTION

The discovery of $J/\psi(3.1)$ in hadronic collisions [1] and in e^+e^- annihilations [2] has led to many speculations about the nature of this particle [3]. In particular, the narrow resonance width suggests that the decay is suppressed. This suppression is most probably due to hidden charm [4]. If, instead, J/ψ would carry a new quantum number, its production could show a "delayed" threshold, as in the familiar case of "associated production" of $\bar{p}$, $\bar{K}$, etc. The energy dependence of the J/ψ cross-section gives us information on the production mechanism [5,6].

Until now, production cross-sections for $J/\psi(3.1)$ near threshold have been measured on nuclei only. Because of possible collective nuclear effects it is difficult to draw conclusions about kinematic thresholds; therefore a measurement at low energies on a hydrogen target is of interest. In the reaction

$$p + p \rightarrow J/\psi + X$$

at 24 GeV/c, the momentum of the CERN Proton Synchrotron (PS) slow extracted proton beam, the mass of X cannot exceed 3.74 GeV/c². Therefore, assuming baryon conservation, the mesonic or baryonic components of X cannot have masses greater than 1.87 or 2.8 GeV/c², respectively. Thus the production of a charmed meson pair with a total mass of 3.7 GeV/c² is excluded *a priori* [7].

The most favourable experimental conditions for detecting rare heavy resonances decaying into two charged particles are met when these particles are produced at rest in the c.m. system of the collision and when their decay products, emitted around 90° in the c.m. system, are detected [8]. In these conditions, the decay particles have high transverse momentum, whereas the background of secondary hadrons and leptons in the collision is dropping fast with increasing transverse momentum. A bispectrometer with two identical focusing branches has been used in this experiment for the measurement of the production of J/ψ through their lepton decay channels.

2. EXPERIMENTAL SET-UP

The 24 GeV/c s_7 external proton beam from the CERN PS was focused onto a target (liquid H_2 , carbon, or tungsten).

The emission angle in the laboratory system of particles emitted at 90° in the c.m. of the collision is about 278 mrad for 24 GeV/c incident protons. They are collected and identified in a bispectrometer shown schematically in Fig. 1. The steering magnet M_0 placed just after the production target served to bend the particle trajectories inward. It was needed because there was not enough space available in the experimental area to install both arms at an angle of 278 mrad to the beam line; these arms were aligned at a fixed angle of 195 mrad. The magnet steered into the spectrometers particles emitted from the target at a mean angle of 265 mrad, i.e. with a small longitudinal momentum of 0.1 GeV/c. This auxiliary magnet limited the use of the bispectrometer to the detection of oppositely charged pairs of particles. After M_0 , two quadrupole triplets focused the desired particles into parallel beams about 18 cm in diameter. Finally, two magnets, with horizontal field, bent the beams upward to leave the hot production area through pipes in the PS shielding at 40 mrad with the horizontal. Particles were travelling in vacua from the target up to the exit of the shielding wall. The residual primary beam was absorbed in an iron and concrete dump placed between the magnetic elements of the two spectrometers.

The choice of focusing spectrometers allowed the use of a very compact detection system which was completely located outside the PS shielding wall. The reduction in noise level was, however, made at the expense of a somewhat reduced momentum acceptance.

The intensity of the incoming beam was typically 10^{12} protons per 350 ms burst. The beam intensity was monitored by a calibrated secondary emission chamber (SEC) with a large sensitive area. The position and shape of the beam were checked by closed-circuit TV. Under normal conditions for liquid-hydrogen target runs the size of the focus at the production target was about 0.2 mm high and 5 mm wide

with a vertical divergence of ± 10 mrad and a horizontal divergence of ± 1 mrad. However, for the runs with solid targets (C, W), the size of the primary beam was increased by an additional transmission target for another experiment upstream in the beam line. In these cases, only a fraction of the beam actually hit the target, since the vertical dimension of the target had to be kept small enough in order not to spoil the momentum resolution of the spectrometer. The number of interacting protons was monitored by two telescopes, which recorded secondaries at approximately 90° with respect to the incoming beam. The fraction of effective beam intensity was determined in special runs, using targets with large lateral dimensions. In this case, the monitor rate is proportional to the beam intensity as measured by the SEC, and to the target thickness. Effects, such as background rate due to the beam halo, have been corrected for. Taking uncertainties of the above-mentioned procedures into account, the intensity of incoming protons hitting the target is known with an accuracy of $\pm 15\%$.

Three types of targets have been used:

- i) A liquid H_2 target consisting of a cylinder 18 cm long and 3 cm in diameter. The windows were 0.2 mm steel foils. The hydrogen was supercooled with liquid helium. Forced circulation ensured that heat removal was large enough to prevent bubble formation inside the target volume.
- ii) A carbon target 10 mm long, 2 mm high, and 5 mm wide.
- iii) A tungsten target composed of five sheets of 0.4 mm thickness, 4.5 mm high, and 10 mm wide. They were spread over a distance of 16 cm along the beam line in order to reduce the amount of matter crossed by the particles emitted into the spectrometer.

The solid targets were suspended by thin wires.

The detectors in each arm were hodoscopes and proportional chambers for track reconstruction, threshold Čerenkov counters for particle identification, scintillation counters ("timing counters") for precise measurement of the time difference between particles in each arm of the spectrometer, and finally, a stack of four lead-glass shower counters (Fig. 1).

a) Timing counters

These counters were placed at a distance of 25 m from the target. Each consisted of 12 scintillators, $2 \times 2 \text{ cm}^2$ in cross-section and 25 cm high. They were viewed from each side by fast XP 2020 photomultipliers, six in total for each arm of the spectrometer. The signals were mixed, and the time definition was provided by a zero crossing discriminator. The resolution was $\pm 0.3 \text{ ns}$. The width of the time window for triggering was set to 10 ns [9].

b) Particle identification (electrons against hadrons)

For the J/ψ measurement, electrons were identified by threshold Čerenkov counters. These had a length of 2.70 m containing CO_2 at a pressure such that the electron Čerenkov light emission angle was 15 mrad. The Čerenkov light was focused by a spherical mirror into a 2" photomultiplier. Additional information for electron identification came from a stack of four lead-glass counters. The total thickness was 20 radiation lengths. Each octagonal block was viewed from the sides by eight photomultipliers. The pulse-height resolution was typically 10%, and was mainly determined by the beam rate. For hadron rejection it turned out to be sufficient to set a lower threshold at about half of the average pulse height of electrons. The effective combined rejection ratio of hadron pairs against electron-positron pairs was $\sim 10^{-8}$.

c) Tracking devices

In each arm the particles left the vacuum system 17 m after the target and went through two sets of x-y hodoscopes and x-y multiwire proportional chambers (1 mm spacing). The two sets were separated by 200 cm. The width of each hodoscope counter was 8 mm. The signals from these hodoscope counters were incorporated in the fast trigger logic. Additionally, they passed a hard wired logic for angular selection and multiplicity rejection. The latter was needed for unique track reconstruction.

3. DATA TAKING

During the J/ψ measurements, the bispectrometer was tuned for a central mass of $3.1 \text{ GeV}/c^2$. In this case, its magnetic elements and the Čerenkov counters were set at a nominal momentum of $5.9 \text{ GeV}/c$. Individual counting rates were 1.2×10^6 and 3.6×10^6 counts per second in the negative and positive branches, respectively.

Electron events were written on tape if they satisfied the following trigger conditions: a) multiplicity and angular constraints in multiwire chamber; b) threshold Čerenkov counter fired; c) coincidence ($\pm 5 \text{ ns}$) between the timing counters. This trigger does not involve the information from the lead-glass counters, which is used during the off-line analysis only.

The time interval of 10 ns contains the events together with many accidental coincidences in which both detected particles are not causally connected. For each trigger the time difference at the timing counters was digitized in 0.1 ns intervals and recorded. The time difference spectrum shows a peak of real coincidences N_c superposed on a continuum of accidentals N_a . The peak-to-background ratio is a measure of the correlation coefficient ρ , defined by

$$\rho = \frac{d^4 N_{1,2}/(d\Omega_1 dp_1 \times d\Omega_2 dp_2)}{(d^2 N_1/d\Omega_1 dp_1)(d^2 N_2/d\Omega_2 dp_2)} - 1 .$$

Here $d^4 N_{1,2}/(d\Omega_1 dp_1 \times d\Omega_2 dp_2)$ is the differential rate for two-particle emission per interacting proton, and $d^2 N_{1,2}/d\Omega dp_{1,2}$ the corresponding rate for one-particle emission [8]. The measured ratio N_c/N_a is proportional to $(1 + \rho)$ and inversely proportional to the number of interacting particles N_{int} :

$$\frac{N_c}{N_a} = \frac{C \times (1 + \rho)}{N_{\text{int}}} ,$$

where C is a constant of the spectrometer. A bump in the ρ distribution as a function of the spectrometer momentum setting (p_1, p_2) signals a resonance, corresponding to a mass

$$m_R \approx [2 \times p_1 p_2 (1 - \cos \theta_{1,2})]^{1/2} .$$

The correlation of the hadron continuum in the investigated region has been measured to be $\rho \lesssim 4$ [8]. In our experimental conditions, this gives $N_c/N_a \sim 0.06$ for a rate of 2.5×10^{10} interacting protons/burst. This ratio must be of the same order of magnitude for the electron continuum, since most electrons are indirect products of π^0 decays. With the spectrometer set to $m_R = 3.1 \text{ GeV}/c^2$, a prominent peak appears on the e^+e^- time difference spectrum, with $N_c/N_a > 4$. Since no such coincidence signal is seen with the spectrometer momentum set either above or below $3.1 \text{ GeV}/c^2$, the J/ψ is detected.

Even with the not very tight trigger described above, the data-taking rate was a few hundred electron events per day only. In order to check the stability of the equipment, the trigger rate was increased to about one per burst by allowing pion signals from one arm of the spectrometer in the 10 ns coincidence window.

The total running time for the experiment as presented in this paper amounts to ~ 70 days. The number of incident protons as used for the cross-section calculation is given in Table 1, third row.

4. DATA ANALYSIS AND RESULTS

The first step of the data analysis is to include the lead-glass counter information. The following cuts were applied (Fig. 2):

- a) $E_{\text{left}} \geq 3.85 \text{ GeV}$, $E_{\text{right}} \geq 3.85 \text{ GeV}$,
- b) $(E_{\text{left}} \cdot E_{\text{right}})^{\frac{1}{2}} \geq 4.7 \text{ GeV}$,

where E is the energy deposited as measured by the total amount of Čerenkov light in the four lead-glass blocks. The second condition gives a rough lower bound for the e^+e^- invariant mass, since the angle between the electrons does not vary appreciably over the spectrometer acceptance.

The resulting time difference spectra for the different targets at the $3.1 \text{ GeV}/c^2$ setting are shown in Fig. 3. The number of accepted events within the window of 1.2 ns, before and after background subtraction, are given in Table 1, first and second row, respectively.

Signal-to-background ratios are 3.8 for hydrogen, 10.8 for carbon, and 4.7 for tungsten targets.

With the momentum reconstruction of the events, it is possible to check the distribution of the invariant mass. The efficiency of each proportional chamber being about 96% the total reconstruction efficiency was about 70%. The resulting mass distribution is centred at $3.1 \text{ GeV}/c^2$ with a standard deviation of $100 \text{ MeV}/c^2$. There are essentially three sources contributing to the error:

- i) uncertainty due to the MWPC resolution, as reproduced by Monte Carlo calculations, $\pm 50 \text{ MeV}/c^2$;
- ii) multiple scattering contributes $\pm 30 \text{ MeV}/c^2$;
- iii) extended beam size (for H_2) or target size is estimated to contribute $\pm 60 \text{ MeV}/c^2$.

These uncertainties account for the width of the experimental mass distribution.

The acceptance of the bispectrometer was calculated by Monte Carlo methods for each of the targets. Indicative numbers for each arm are $1.2 \times 10^{-3} \text{ sr}$ for the angular acceptance of the quadrupole triplet, and $\Delta p/p = 10^{-1}$ for the momentum band. Combining the information from the two spectrometer arms, the limits of acceptance for $J/\psi \rightarrow e^+e^-$ are $0.02 \text{ GeV}/c$ and $0.24 \text{ GeV}/c$ for longitudinal momentum in the c.m. system, and $|p_T| \leq 0.3 \text{ GeV}/c$ for transverse momentum (the numbers indicate momenta for which acceptance is reduced to $\sim 10\%$ of maximum). The accepted volume in J/ψ momentum space is approximately

$$(\Delta p)^3 = 0.013 (\text{GeV}/c)^3 .$$

This number multiplied by the angular acceptance gives the total acceptance.

The main quantities for the cross-section calculation are collected in Table 1. The total number of effectively contributing incoming protons is listed in the third row. There are additional factors, such as over-all hodoscope efficiencies (64%) and the loss from rejection of multiple events, which ranges from 45% to 55% depending on running conditions. Assuming a flat longitudinal momentum distribution and a transverse momenta distribution of the form $\exp(-ap_T^2)$ for isotropically

decaying J/ψ , the acceptance as calculated by the Monte Carlo program varies with the target geometry [$a = 1.6 \text{ (GeV/c)}^{-2}$] [9]. The values are given in the fourth row of Table 1.

The resulting differential cross-sections for the e^+e^- decay channel of the J/ψ are given in Table 1, row 5.

For comparison with measurements reported by other authors the total production cross-section has been calculated using an $\exp(-1.6p_T^2)$ transverse momentum distribution as measured by the MIT-BNL group [10], and a longitudinal momentum distribution which is constant up to $x = 0.3$ and which varies like $\exp(-6x)$ for larger x , as measured in Serpukhov [11] [where $x = p_L(\psi)/p_{\text{max}}$ is the Feynman variable]. The total cross-sections are listed in the sixth row. The branching ratio for $J/\psi \rightarrow e^+e^-$ is taken as $6.9 \pm 0.9\%$ [12].

Shorter runs were also made at 2.8 GeV/c^2 with the H_2 target, and at 3.8 GeV/c^2 with a carbon target. There was no visible coincidence signal. In order to compare these cross-section limits with the production cross-section for 3.1 GeV/c^2 on H_2 , the cross-section of the 3.8 GeV/c^2 measurement has been rescaled according to the power law as evaluated at the end of this paper. The cross-sections (times the branching ratio in e^+e^-) of a hypothetical resonance in these mass regions have been estimated to be

$$\text{at } m = 2.8 \text{ GeV/c}^2: E \frac{d^3\sigma}{dp^3} = 0.008 \pm 0.017 \text{ nb/GeV}^2/\text{c}^3 ;$$

$$\text{at } m = 3.8 \text{ GeV/c}^2: E \frac{d^3\sigma}{dp^3} = 0.003 \pm 0.003 \text{ nb/GeV}^2/\text{c}^3 .$$

Thus the contribution of the lepton continuum at the spectrometer setting for the J/ψ resonance is smaller than the statistical error quoted in Table 1. In addition, it is known from other experiments at higher energies that the continuum of lepton pairs at J/ψ resonance is negligible [13,14].

A measurement of the J/ψ cross-section detecting the $\mu^+\mu^-$ channel has also been performed. At a distance of 2 cm from the target, a hadron absorber (74 cm

copper) was introduced in both arms. The energy loss of the μ 's was 1.2 GeV. Multiple scattering in the absorber reduced the acceptance considerably. This could be compensated only partially by increased target thickness. Muons were identified as such by threshold Čerenkov counters and as minimum ionizing particles by the lead-glass counters; additionally they were required to pass through 80 cm of iron at the far end of the spectrometer arms. Thus a real coincidence signal is recorded for two targets, carbon and lead, with peak-to-background ratios of 10 and 3, respectively (Fig. 4). The extracted cross-sections based on 21 events for C and 17 events for Pb are:

$$C : BR \times E \frac{d^3\sigma}{dp^3} = (0.37 \pm 0.18) \frac{\text{nb/nucleus}}{\text{GeV}^2/c^3} ;$$

$$Pb : BR \times E \frac{d^3\sigma}{dp^3} = (5.2 \pm 2.6) \frac{\text{nb/nucleus}}{\text{GeV}^2/c^3} .$$

As compared with the cross-section for the e^+e^- decay channel, they are in good agreement, since the branching ratios for $\mu\mu$ and ee are the same [12]. Because of the large errors and remaining uncertainties for the acceptance, in the following only the e^+e^- measurements are considered.

5. CONCLUSIONS

This experiment establishes that the J/ψ is produced on hydrogen by 24 GeV/c protons at a rate which is not considerably lower than on nuclei.

Assuming a power law

$$\sigma_{\text{tot}} \propto A^\alpha$$

for production of J/ψ on nuclei of atomic number A , the present measurements for $A = 1, 12$, and 185 are fitted with the value

$$\alpha = 0.92 \pm 0.09 \quad (\text{Fig. 5})$$

for the exponent. This number compares well with $\alpha = 0.93 \pm 0.04$ as derived from neutron-induced J/ψ production on nuclei at FNAL [13]. This large value of α is in agreement with the small J/ψ -nucleon total cross-section, as measured in J/ψ

photoproduction experiments [15]. Using only the carbon and tungsten measurements for parametrization of the A-dependence, the extrapolated value for the hydrogen production cross-section is 40% higher than the measured cross-section; however, it is still lying rather near the limit of one standard deviation.

The effect due to Fermi motion could be estimated if the energy dependence of the J/ψ production cross-section on nuclei were known. As a first approximation we take the energy dependence given by Donnachie and Landshoff [6], which describes the J/ψ -nucleon cross-sections, as measured so far, rather well. A calculation of the differential cross-section yields $(d\sigma/dy)_{y=0} = 0.8$ nb at 24 GeV/c [16]; this lies on top of our measured cross-section for hydrogen, using the parametrization of the p_T distribution from Ref. [11]. The increase of cross-section in nuclei due to the increase of effective centre-of-mass energy, is about 20%. The measured cross-section on hydrogen is displayed in Fig. 6 together with the cross-sections of other experiments at various energies.

This experiment shows that the cross-section of J/ψ on hydrogen is not significantly lower than the extrapolated value using the power law for the A-dependence. It also shows no appreciable enhancement due to Fermi motion, and therefore absence of "delayed" threshold effects.

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Table 1

	H	C	W
Events in the time window	46	43	28
Continuous background subtracted	37.5	36.2 ^{b)}	23.6
No. of incident protons	10.1×10^{17}	3.8×10^{17}	2.4×10^{17}
Acceptance in $(\text{GeV}/c)^3$	1.76×10^{-5}	2.21×10^{-5}	1.90×10^{-5}
$\text{BR} \times E \frac{d^3\sigma}{dp^3} \left[\frac{\text{nb/nucleus}}{\text{GeV}^2/c^3} \right]$	0.028 ± 0.008 ^{a)}	0.36 ± 0.09	(3.7 ± 1.0)
$\sigma_{\text{tot}} [\text{nb}]$	0.56 ± 0.16 ^{a)}	7.2 ± 1.8	(74 ± 20)

a) 7% correction for J/ψ -production on the windows of H_2 -target included.

b) Among these events, 14 have been obtained using a 3 cm thick carbon target and under slightly different experimental working conditions. They do not appear in Fig. 3.

Figure captions

- Fig. 1 : Layout of the experiment. T: target; M_0 : horizontal bending magnet; Q1-Q3: quadrupoles; M 1: analysing magnets; H_{xy} : hodoscopes and MWPC's; $\check{C}$: threshold Čerenkov counters; TC: timing counters. Pb-glass: shower counters.
- Fig. 2 : Lead-glass counter spectra for electrons (a) and positrons (b), all runs summed for the spectrometer setting on $3.1 \text{ GeV}/c^2$. Hatched region indicates accepted events.
- Fig. 3 : (e^+e^-) -time difference spectra for the hydrogen (a), carbon (b), and tungsten (c) targets. Hatched region indicates the accepted time window.
- Fig. 4 : $(\mu^+\mu^-)$ -time difference spectra for carbon (a) and lead (b).
- Fig. 5 : A-dependence of the differential cross-sections for the e^+e^- measurements.
- Fig. 6 : Dependence of the total J/ψ cross-section on the c.m. energy. The curve is taken from Ref. [6]. The symbol $\odot$ indicates our measurements. The other values are extracted from Refs. [10], [11], [13], [14], and [17]; when not given by the authors themselves, the total cross-section has been calculated assuming the same phase-space distribution and branching ratio as those used in this paper (results marked with a $\blacktriangle$ are given without errors in the original paper).

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6