Measurement of J/ψ and ψ' real photoproduction
on Lithium-6 at a mean energy of 90 GeV

NA-14 COLLABORATION

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ABSTRACT

Inelastic and elastic $J/\psi(3097)$ photoproduction on Li^6 are measured at a mean γ energy of 90 GeV in an open spectrometer. The J/ψ are identified by their decays into $\mu^+\mu^-$ or e^+e^- . A signal of $\psi'(3685)$ into $\mu^+\mu^-$ and $J/\psi \pi^+\pi^-$ is also seen. The inelastic cross-section with $Z=E_\psi/E_\gamma < 0.9$ is compared in shape and magnitude with the colour singlet model of photon-gluon fusion.

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1 - Introduction

The production of heavy flavour bound states by real and virtual photons has been extensively discussed in the context of perturbative QCD. The large mass of charmed quarks ($m_c \sim 1.5 \text{ GeV}/c^2$) leads to a small enough $\alpha_s(m_c^2)$, the strong coupling parameter, to justify the use of perturbation theory. The lowest order QCD process is the gamma-gluon fusion process $\gamma g \rightarrow c\bar{c}$. Observation of sizeable inelastic J/ψ production, where inelasticity is usually measured by $Z = E_{J/\psi} / E_\gamma$, led to the proposition of next to leading order QCD subprocesses like $\gamma g \rightarrow c\bar{c}g$ as the source of these events. Calculations using a specific wave-function to describe J/ψ as a $c\bar{c}$ system [1] lead to predictions for the Z and p_T dependence of inelastic J/ψ photoproduction.

This paper describes the properties of the production of J/ψ and ψ' by real photons of incident energy $\langle E_\gamma \rangle \sim 90 \text{ GeV}/c$. Particular emphasis is put on the study of inelastic J/ψ production using a data sample which is an order of magnitude larger than that obtained by previous photoproduction experiments.

2 - The experiment

The experiment has been performed in the NA14 open spectrometer fed by the E12 $e\gamma$ beam at the CERN SPS. E12 is a bremsstrahlung photon beam generated from a broadband electron beam of mean energy 140 GeV and of intensity $10^8 \text{ e}^-/\text{SPS pulse}$ crossing a 10 % X_0 radiator. The photon beam, tagged between 50 and 150 GeV, impinges on a 10 % X_0 Li^6 target.

The NA14 spectrometer described in more detail elsewhere [2] has a large angular acceptance to charged particles and photons of up to 300 mrad in the laboratory.

The muon identifier is located downstream of the forward calorimeter FC (Fig. 1). It consists of 3.8 m of iron sandwiching two horizontally and one vertically segmented scintillator hodoscopes allowing identification of muons with polar angles below ~ 80 mrad.

The trigger on J/ψ decaying into a muon pair requires the coincidence of a minimum bias pretrigger with two "roads" in the muon identifier. The roads are defined by coincidence patterns among three sets of horizontal slabs such that only tracks coming from the target region are accepted. This reduces the rate of triggers arising from the muon halo ($\sim 10^6 \mu/m^2$ /SPS pulse). More details on the analysis of data from this trigger can be found in [3].

The trigger on J/ψ decaying into an electron pair is based on a local energy deposition in the forward electromagnetic calorimeter. Details of the analysis of di-electron data can be found in ref. [4].

3 - Data Reduction

The results presented have been extracted from $\sim 190K$ dimuon triggers satisfying the above mentioned conditions. These events were processed through the geometry program TRIDENT. Events having a good vertex in the target were kept for subsequent analysis. Further cuts were made on track quality to purify the sample. These cuts were designed to remove halo muons and electromagnetic background (eg. pairs) which appeared at random in the strobe gate (100 ns) of the MWPC's.

Tracks were identified as muons if their extrapolation from the MWPC into the muon identifier coincided with the observed road of hits in the hodoscopes. Events containing at least two muons so validated and consistent with the dimuon trigger were retained.

Triggers on local high P_T electromagnetic energy deposits seen by the forward electromagnetic calorimeter were used to study the J/ψ particle decaying into e^+e^- . Electrons were filtered off line using a fast procedure which incorporated the information from the MWPC placed on each side of the M_2 magnet. The candidates were mainly electrons from γ conversions and hadrons. The hadrons were removed by an E/p cut. Those candidates which by association to another charged track formed an electromagnetic pair were also discarded. Events with 2 electron candidates, at least one satisfying the trigger condition, have been selected for further analysis.

4 - J/ψ and ψ' signal

The effective mass of all $\mu^+\mu^-$ combinations above $1.3 \text{ GeV}/c^2$ is shown in Fig. 2.a. There is a clear J/ψ signal and good evidence for the ψ' . We have fitted the resonances by Gaussian functions, with a common width for J/ψ and ψ' , over a smooth background.

The results of the fit are listed below.

	Mass (MeV/c^2)	σ_M (MeV/c^2)	Nb. of events
J/ψ	$3092. \pm 2.$	$40. \pm 2.$	1272 ± 37
ψ'	$3698. \pm 13.$	$40. \pm 2.$	23 ± 5

Opposite sign dimuons were labelled as J/ψ 's and used in the following analysis if $|M_{\mu^+\mu^-} - M_{J/\psi}| < 160 \text{ MeV}/c^2$. The number of J/ψ in this range is found to be 1275 including a background of 3.2 %.

ψ' is also observed in the channel $\psi' \rightarrow J/\psi \pi^+\pi^-$, with $J/\psi \rightarrow \mu^+\mu^-$. Fig. 3 shows the effective mass plot for the 4 prong ($\mu^+\mu^- \pi^+\pi^-$) events with $M_{\mu\mu} = M_{J/\psi}$ and no additional energy recorded. We have assumed that all detected particles, except identified muons, were pions.

The dielectron mass spectrum is shown in Fig. 2b after correcting the electron momenta for bremsstrahlung photon radiation as measured in the calorimeters. There is a clear J/ψ signal of ~ 200 events.

5 - Acceptance Determination

The spectrometer acceptance for dimuon pairs was determined by a Monte-Carlo program in which :

- i) the beam energy spectrum determined from the observed spectrum of tagged photons corrected for multiple bremsstrahlung in the radiator was used.
- ii) the measured MWPC's efficiencies, the effect of the desensitized regions in the horizontal plane, the multiple scattering of μ 's in the iron of the muon identifier, the target length and the beam characteristics were considered.

The decay angular distribution for the J/ψ , both elastic and inelastic, was assumed to be $(1+\cos^2\theta)$ where θ is the polar angle of μ^+ relative to the beam in the J/ψ rest frame. As we have a very small acceptance for $|\cos\theta| \sim 1$ we cannot verify the above hypothesis.

a) Incoherent elastic J/ψ production ($\gamma N \rightarrow J/\psi N$) :

The J/ψ transverse momentum squared distribution was assumed to have an exponential dependence,

$$e^{-bp_T^2} \quad \text{with } b = 2.5 \text{ (GeV/c)}^{-2}$$

The acceptance was found to be insensitive to the precise value of b .

b) Inelastic J/ψ production ($\gamma N \rightarrow J/\psi X$) :

Here b was taken to be $1. \text{ (GeV/C)}^{-2}$. The J/ψ energy distribution is taken from the $Z = E_{J/\psi} / E_\gamma$ distribution of [1]. The variation of $\sigma_{\text{INEL}}^{\text{TOT}}$ versus E_γ is also taken from [1] in which the reaction $\gamma N \rightarrow J/\psi + X$ is

assumed to proceed via the subprocess $\gamma g \rightarrow J/\psi g$. In order to take into account the hadronisation of X , we have used the LUND program to hadronise the gluon, the quark and the diquark.

For accepted Monte-Carlo events the multiplicity and momentum distributions are found to be in agreement with those observed in the data sample.

c) Elastic ψ' production ($\gamma N \rightarrow \psi' N$) with $\psi' \rightarrow J/\psi \pi\pi$:

Assumptions similar to the ones for elastic J/ψ production were made. The decay distribution of the dipion system in the $\psi' \rightarrow J/\psi \pi\pi$ channel was taken to be the one found by the WA11 experiment [5].

d) Bethe-Heitler production :

We have used the formula of Tsai as described in [6]. We stress here the fact that this process is purely electromagnetic and thus perfectly calculable.

6 - Normalisation

The absolute normalisation is obtained by three independent methods which mutually agree within errors. They use :

i) a downscaled hadronic interaction trigger that is sensitive to a known fraction of the total hadronic cross-section and whose real hadronic content is determined offline.

ii) the integrated flux of electrons from which the photon flux is deduced.

iii) the measurement of Bethe-Heitler production on Li^6 with dimuon masses in the range $1.2 - 2.8 \text{ GeV}/c^2$. This method has the advantage that most of the efficiencies and acceptances are common to both J/ψ and Bethe-Heitler samples.

Dimuon events that are produced via the Bethe-Heitler mechanism in the mass range 1.2 and 2.8 GeV/c² are isolated by requiring that :

- i) there are no particles accompanying the dimuon pair.
- ii) the pair has $p_T^2 < 0.1 \text{ (GeV/c)}^2$. The background coming primarily from π and K decays and μ -halo is estimated to be negligible. (No events are found under the same conditions for same sign μ pairs).
- iii) both μ are in regions of good acceptance.

The mass and transverse momentum distribution of the Bethe-Heitler pairs are in good agreement with Monte-Carlo expectation. Fig. 4 shows the differential luminosity extracted from these pairs ; the solid curve gives the same quantity determined by the other methods described above. We estimate that the systematic uncertainty in the normalisation is ~20%.

The data presented here for the dimuons trigger correspond to a sensitivity of 2160 evts/nb with $E_\gamma > 25 \text{ GeV}$. The sensitivity for the electrons trigger is 1150 evt/nb.

7 - Results from the dimuons trigger

a) Ratio of J/ψ and ψ' production

This ratio can be obtained directly from the mass plot (Fig.2) and from the acceptance and various efficiencies given by the Monte-Carlo. Using the branching fractions of J/ψ and ψ' into $\mu^+\mu^-$, 7.4 % and 0.8 % respectively [7], we obtain :

$$\frac{\sigma (\gamma N \rightarrow \psi' X)}{\sigma (\gamma N \rightarrow J/\psi X)} = 19 \pm 4 \%$$

The error quoted is statistical only. This value is in fair agreement with the one deduced from our $\psi' \rightarrow J/\psi \pi^+ \pi^-$ signal : the $\psi' \rightarrow J/\psi \pi^+ \pi^-$ is clearly seen (fig. 3) for elastic ψ' and also for inelastic ψ' production.

b) Elastic J/ψ production

Events were classified as elastic if no charged or neutral track accompanied the J/ψ (846 events found). Monte-Carlo studies show that the recoil proton is not seen in our spectrometer ; also in events corresponding to diffractive target dissociation only the $\mu^+\mu^-$ pair is seen and are hence classified as elastic. An independant check of the elasticity is provided by the tagging informations when the incident e^- radiates only a single high energy γ . In this case the tagging system allows a measurement of the energy balance. The elastic peak in $(E_\gamma - E_{J/\psi})$ indicates a resolution of 2 GeV.

The p_T^2 distribution for elastic J/ψ events, corrected for acceptance is shown in Fig. 5a. A clear coherent production peak is observed for $p_T^2 < 0.2 \text{ (GeV/c)}^2$. We have fitted the distribution with the formula :

$$\frac{dN}{dp_T^2} = A e^{-ap_T^2} + B e^{-bp_T^2} + C e^{-cp_T^2}$$

and found $a = 25.0 \pm 2.3$ for coherent production
 $b = 2.5 \pm 0.2$ for incoherent production
 $c = 0.6$ (fixed) to represent the inelastic
 feedthrough as described below.

In order to compute absolute cross-section for incoherent elastic J/ψ production, with the above definition, we have considered :

- I) the geometrical acceptance, trigger and reconstruction efficiencies.
- II) the removal of coherent production.
- III) the subtraction of background under the J/ψ peak for elastic events, which is found to be $\sim 3 \%$.
- IV) the removal of feedthrough from $\psi' \rightarrow J/\psi \pi\pi$ events, with $J/\psi \rightarrow \mu^+\mu^-$, where all tracks accompanying the J/ψ are lost or not found by the reconstruction. The level of feedthrough was evaluated by Monte-Carlo and normalised to the observed number of $\psi' \rightarrow J/\psi \pi^+ \pi^-$ with $J/\psi \rightarrow \mu^+\mu^-$, taking into account that $(\psi'_{\text{INEL}} / \psi'_{\text{EL+INEL}})_{\text{observed}}$ is found to be $\sim 30 \%$. This correction is small : less than 3 %.

V) the removal of inelastic events that were seen as elastic because tracks accompanying the J/ψ had been lost. The contribution was evaluated by Monte-Carlo for inelastic events as outlined above. We estimate that :

$$\frac{\psi_{inel} \rightarrow \psi_{el}}{(\psi_{inel})_{observed}} = 25 \%$$

The corresponding number (64 events) is in good agreement with the magnitude found for the term $Ce^{-0.6p_T^2}$ (see above) and this explains why we call it the inelastic feedthrough.

VI) the addition of elastic events which were classified as inelastic due to background tracks (i.e. charged tracks in the MWPC time gate or showers initiated by halo muons). This was evaluated by using the Bethe-Heitler dimuons sample. Approximately 4 % of the elastic events have been wrongly classified as inelastic.

Taking the above corrections into account we estimate that

$$i) \quad \frac{\psi_{el}^{coh}}{\psi_{el}^{all}} = 41.6 \% \pm 3 \%$$

The error quoted is statistical only.

ii) The incoherent elastic J/ψ production cross-section has been extracted for various beam energies (Fig. 6a). For comparison we also show the cross-sections extracted by other experiments. We estimate that the elastic incoherent cross-section is 12.8 ± 2 nb/nucleon at our mean energy of 90 GeV. A linear A dependance has been assumed. Systematic errors arising from luminosity determination, Monte-Carlo inputs and subtraction procedures are estimated to be of the order of 25 %.

c) Inelastic J/ψ production

Events were classified as inelastic if at least a charged or neutral track accompanied the J/ψ (423 events found).

In the determination of the p_T^2 distribution for inelastic events we have taken into account :

- i) the acceptance correction, trigger and reconstruction efficiencies,
- ii) the removal of events arising from $\psi' \rightarrow J/\psi \pi\pi$, using the p_T^2 distribution of J/ψ as evaluated by Monte-Carlo.
- iii) the removal of the background under the J/ψ peak (3 %).

After these corrections a tiny coherent peak is still present. This peak can be explained by elastic events falsely identified as inelastic due to the presence of background tracks. The p_T^2 distribution for these events was assumed to be the same as the one for elastic events. We have then fitted the corrected p_T^2 distribution with the formula :

$$\frac{dN}{dp_T^2} = \alpha \left[A e^{-25 \cdot p_T^2} + B e^{-2.5 p_T^2} \right] + \beta e^{-c p_T^2}$$

The two first terms with slopes characteristic of elastic coherent and incoherent elastic scattering represent elastic events falsely identified as inelastic. The fit indicates that this contribution is less than 10% of the inelastic events. It corresponds to the events considered in paragraph 7bVI. Fig. 5b shows the data for the p_T^2 distribution ; the solid curve corresponds to the fit described above and the dashed curve indicates the contribution of the two first exponentials of the above formula.

The last term $\beta e^{-c p_T^2}$ represents the truly inelastic events ; the corresponding slope is $c = 0.62 \pm 0.2$.

The Z distribution is shown in Fig. 7. This distribution is obtained from the experimental distribution of $Z' = E_\psi / E_{TOT}^{OBS}$ where E_{TOT}^{OBS} is the total observed energy including the energy carried by the J/ψ. All the above mentioned corrections have been taken into account. We have used

the Monte Carlo generating inelastic events to evaluate the migration or smearing between Z' and Z and to perform the acceptance correction. For comparison we also show the Z distribution given by other experiments and the prediction from the model of Berger and Jones [1]. The region $Z < 0.9$ is claimed in [1] to be the region of applicability. In this region, the fraction of inelastic production in our data, which is wrongly assigned to the inelastic sample, amounts to less than 3 % and the mean migration in Z is less than 0.06. We estimate that in the region $Z < 0.9$ the overall systematic uncertainty including normalisation is 25 %. However above $Z = 0.95$ this uncertainty should be increased due to the imperfect separation of the two classes of events. This latter statement is probably true for all experiments.

The inelastic J/ψ photoproduction cross-section has been computed for various beam energies and for $Z < 0.9$ and is shown in fig. 6b. Also shown is the curve obtained from the colour singlet model of Berger and Jones [1] after multiplication by a factor 3.7. This curve would give a reasonable agreement with data, once systematic uncertainties, are taken into account.

d) Limits on χ production

We have looked for χ signal using the decay $\chi \rightarrow J/\psi \gamma$, $J/\psi \rightarrow \mu^+ \mu^-$. The photon is measured in the forward electromagnetic calorimeter. Since the χ particles have different quantum numbers from the incident photon we expect different production mechanisms from the ones seen for the J/ψ and ψ' .

i) $\gamma N \rightarrow \chi N$ production

Diffraction χ photoproduction is not expected on the basis of the χ quantum numbers. But to give a limit on the channel $\gamma N \rightarrow \chi N$ we have assumed that the χ has the same kinematical characteristics as a J/ψ diffractively produced and that it decays isotropically. Events containing only a J/ψ and a single γ with energy higher than 5 GeV have been

selected. We have no candidate for χ_1 (3510) or for χ_2 (3555). The corresponding upper limits at 90 % confidence level on χ elastic production relative to J/ψ incoherent elastic production are :

$$(\chi_1/J/\psi) \text{ el.} < 7 \%, (\chi_2/J/\psi) \text{ el.} < 27 \%.$$

ii) Inelastic χ production

We have assumed that inelastic χ production occurs with the same Z dependence as measured for the J/ψ ; with the above mentioned cuts on the photon energy and the same hypothesis for the χ decay, we have obtained the following upper limits at 90 % confident level.

$$(\chi_1/J/\psi) \text{ inel.} < 15 \%, (\chi_2/J/\psi) \text{ inel.} < 27 \%.$$

8 - Results from the electron trigger

An independent analysis of the 200 J/ψ seen in e^+e^- (fig. 4) has been performed [4]. The relative importance of the three mechanisms leading to J/ψ production : coherent, incoherent elastic and inelastic, has been determined and found to be in agreement with the results from the dimuon data. In particular, integrating over the incident beam energy and selecting inelastic J/ψ events with $Z < 0.9$, we measure a cross section which is in agreement with our $\mu^+\mu^-$ measurement and equals $4. \pm 1. \pm 1.$ times the ones given in [1].

9 - Conclusion

This paper presents a high statistics measurement of inelastic J/ψ photoproduction using real photons. The precise separation of elastic and inelastic J/ψ (see table I) is possible due to the exclusive reconstruction of events allowed by the NA14 spectrometer. The energy dependence of the cross section, the transverse momentum and fractional (Z) momentum distributions are reasonably described by the model of Berger and Jones [1]. The absolute cross section, however, is found to be ~ 4 times higher than the prediction. Although the above disagreement remains a problem, it is well known that the absolute normalization is rather sensitive to the values chosen for the charmed quark mass m_c . Relativistic corrections to the J/ψ wave function and higher order QCD effects may also be important [12]. The level of accuracy of the experimental data clearly calls for more detailed theoretical investigations.

ACKNOWLEDGEMENTS

We sincerely thank the technical staffs of the Institutes collaborating in NA14 for their invaluable contributions and are particularly indebted to L. Andersson, H. Atherton, C. Aubret, L. Bassi, F. Berny, G. Bouvard, W. Cameron, N. Doble, G. Dubail, G. Dubois-Dauphin, R. Ferlicot, C. Fritsch, J.P. Grillet, R. Harfield, D. Miller, J. Movchet, J. Pascual, J. Poinsignon, C. Sobczynski, J.P. Vanuxem, P. Vergezac. We gratefully acknowledge the work of the authors of our pattern recognition and track fitting program F. Carena, F. James, J.C. Lassalle and S. Pensotti. We thank R. Collet for assistance in tape handling. Finally we would like to thank E. Lustière for preparing the manuscript.

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T A B L E I
SUMMARY OF NA14 RESULTS FOR J/ψ PHOTOPRODUCTION ON LITHIUM-6

	Total nb of J/ψ	$\frac{\sigma_{\psi'}}{\sigma_{\psi}}$	ELASTIC (coherent + incoherent) PRODUCTION			INELASTIC PRODUCTION			
			$\frac{\text{COH.}}{\text{COH.} + \text{INCOH.}}$	$\frac{P_T^2 \text{ distribution}}{e^{-bP_T^2}}$ $b_{\text{COH.}} (\text{GeV}/c)^{-2}$	$\frac{P_T^2 \text{ distribution}}{e^{-bP_T^2}}$ $b_{\text{INCOH.}} (\text{GeV}/c)^{-2}$	$\sigma_{\text{TOT}}^{\text{INCOH.}}$ at 100 GeV	$P_T^2 \text{ distribution}$ $e^{-bP_T^2}$ $b_{\text{INEL}} (\text{GeV}/c)^{-2}$	$\sigma_{\text{TOT}}^{\text{INEL}}$ $Z < 0.9$ at 100 GeV	$\frac{\text{exp.}}{\text{Ref. 5}}$ $\frac{\text{inel } Z < 0.9}{\text{EL INCOH.}}$
dimuon trigger	1272	0.19 ± 0.04	0.42 ± 0.03	25.0 ± 2.3	2.5 ± 0.2	$14.0 \pm 1.6 \text{ nb}$ syst. error = $\pm 2.5 \text{ nb}$	0.62 ± 0.20	$10.2 \pm 2.3 \text{ nb}$ syst. error = $\pm 3. \text{ nb}$	0.73 ± 0.2
electron trigger	207	0.39 ± 0.08	30 ± 6		2.5 ± 0.5	$17. \pm 5. \text{ nb}$	0.6 ± 0.3	$11.2 \pm 3. \text{ nb}$ syst. error = $\pm 3. \text{ nb}$	0.66 ± 0.3

Figure Captions

Fig. 1 - Top view of the NA14 spectrometer.

Fig. 2a - Muon pair mass distribution above $1.3 \text{ GeV}/c^2$ for elastic and inelastic events.

Fig. 2b - e^+e^- mass distribution after bremsstrahlung corrections.

Fig. 3 - $\mu^+\mu^-\pi^+\pi^-$ invariant mass for four track events, (elastic ψ') where $M_{\mu^+\mu^-}$ is between 2.9 and $3.3 \text{ GeV}/c^2$.

Fig. 4 - Differential luminosity. The curve indicates the variation of the luminosity versus E_γ as given by the differential flux of incident electrons corrected for single and double bremsstrahlung.

Fig. 5a - P_T^2 distribution for elastic J/ψ events.
The full curve corresponds to the fit described in the text.
The dashed curve indicates the contribution of inelastic events seen as elastics.

Fig. 5b - P_T^2 distribution for inelastic J/ψ events.
The full curve corresponds to the fit described in the text.
The dashed curve indicates the contribution of elastic events misidentified as inelastics.

Fig. 6a - Cross section versus energy for incoherent elastic J/ψ photoproduction. For BPF [8] muoproduction, elastic means : $ECAL < 3. \text{ GeV}$ with corrections. For EMC [9] muoproduction, contribution from ψ' not removed, smearing corrections not made, elastic means : $Z > .95$. For IF [10] photoproduction, elastic means elastic + diffractive target dissociation (hatched zone). For FTPS [11] photoproduction, elastic means forward elastic.

Fig. 6b - Cross section versus energy for inelastic J/ψ photoproduction : all results are for $Z < .9$. The curve is the prediction of [1] multiplied by 3.7.

Fig. 7 - Z distribution for inelastic J/ψ events.
The curve is the prediction of [1] multiplied by ~ 3.7 in order to fit our results for $Z < .9$. For EMC data, contribution of cascade decays from $\psi' \rightarrow \psi x$ has not been subtracted. Smearing corrections due to finite hadronic energy resolution of STAC have not been applied.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7